ML 2014, Chapter 312, Article 12, Section 8 Project Abstract
For the Period Ending December 30, 2019

PROJECT TITLE: MITPPC Sub-project #1 Novel Diagnostic Tools for Rapid and Early Detection of Oak Wilt
PROJECT MANAGER: Dr. Abdennour Abbas
AFFILIATION: University of Minnesota
MAILING ADDRESS: 2004 Folwell Ave., Kaufert Lab, Rm 203
CITY/STATE/ZIP: St. Paul, MN 55108
PHONE: 612-624-4292
E-MAIL: aabbas@umn.edu
WEBSITE: www.abbaslab.com
FUNDING SOURCE: Environment and Natural Resources Trust Fund
LEGAL CITATION: ML 2014, Chapter 312, Article 12, Section 8

APPROPRIATION AMOUNT: $271,911
AMOUNT SPENT: $271,911
AMOUNT REMAINING: $0

Sound bite of Project Outcomes and Results

This project developed a novel, patented Nanoparticles Enhanced Chemiluminescence assay for the rapid detection of the fungus *Bretziella fagacearum* that causes oak wilt disease. Early detection of invasive forest pathogens is expected to have a significant economic impact by preventing the spread of diseases and the conservation of natural resources.

Overall Project Outcome and Results

Oak trees (*Quercus* spp.) play a significant role in the ecosystem and are considered economically important for several reasons. They are prone to oak wilt disease, caused by the fungus, *Bretziella fagacearum*, which is of huge concern due to the reduced profitability in their production. Affected trees cannot be cured and so, early, and rapid identification of the infection is necessary to prevent spreading. The objectives of this study include the development of cell separation method of woodchips and DNA extraction method, followed by the development of a rapid detection assay in combination with a handheld system. Infected and healthy red oak wood chip samples were collected from different parts of Minnesota followed by DNA extraction and testing using the chemiluminescence-based chemical assay. In phases I and II of this project, we developed a novel Nanoparticles Enhanced Chemiluminescence (NEC) assay. The major accomplishments include: **(1)** Combination of the DNA extraction protocol with NEC assay detection. **(2)** Application of the NEC assay on real-world samples (wood chips from healthy and infected red oak trees) and determination of the sensitivity (88.8 %) and specificity (73%) of the NEC assay. **(3)** Optimization of the reaction conditions. Additionally, MITPPC phase III proposal has been approved to expand the NEC assay to various invasive forest pathogens of high priority to Minnesota and conduct third party validation of the technology. The major impact of this project will be the improvement of diagnostic capabilities of plant diagnostic clinics and laboratories by offering a highly sensitive and cost-effective tool for rapid identification of oak wilt. The spread of the disease can be stopped at an early stage by administering treatments and implementing preventative measures. The proposed technology will help protect Minnesota natural resources and reduce the financial burden of oak tree removal.

Project Results Use and Dissemination

Description: The research findings were disseminated through regular updates to the Minnesota Invasive Terrestrial Plants and Pests Center, non-peer reviewed outlets (e.g., newsletters or websites), and peer-reviewed publications. This project was also discussed through formal and informal presentations to stakeholder groups and scientific societies.

ML 2014, Chapter 312, Article 12, Section 8 Project Abstract
For the Period Ending June 30, 2020

PROJECT TITLE: MITPPC Sub-project #2 Early detection, forecasting and management for *Halyomorpha halys*
PROJECT MANAGER: Dr. Bill Hutchison
AFFILIATION: Dept. of Entomology, University of Minnesota
MAILING ADDRESS: 1980 Folwell Ave., 219 Hodson Hall
CITY/STATE/ZIP: St. Paul, MN 55108
PHONE: 612-619-1775
E-MAIL: hutch002@umn.edu
WEBSITE: https://www.fruitedge.umn.edu/pests/bmsb
FUNDING SOURCE: Environment and Natural Resources Trust Fund
LEGAL CITATION: ML 2014, Chapter 312, Article 12, Section 8

APPROPRIATION AMOUNT: $616,081
AMOUNT SPENT: $616,081
AMOUNT REMAINING: $0
Project Team: William Hutchison, Bob Koch, Peter Snyder, Tracy Twine
Post-doctoral training: Byju Govindan (Entomology), Stephan Liess (Soil, Water, and Climate)
Researcher: Eric Burkness (Entomology)

Sound bite of Project Outcomes and Results
This project produced a new app to identify the brown marmorated stinkbug, improved traps for monitoring, and forecasted the range and development of stinkbugs in under future weather scenarios so farmers can anticipate infestations and use less insecticide. Brown marmorated stinkbug is a pest of soybean, corn, and fruit.

Overall Project Outcome and Results
Just before the detection of the Brown Marmorated Stink Bug (BMSB) in Minnesota (2010), this invasive pest had caused approximately $35 million in damage to the apple industry in eastern states. At the time, we knew very little of its biology, how to monitor this pest, how fast it could spread, and to what extent it could damage MN fruit, vegetable and field crops; a total of at least 12 major MN crops are at risk. With this project we were able to achieve several goals. To support early, more efficient detection of BMSB, we helped evaluate a new "Dual-lure" bait and sticky trap that was a huge improvement over previous traps. Likewise, to better forecast BMSB infestations we developed and tested a "heat-unit" or degree-day model. DD models are based on the fact that insects cannot regulate their body temperature (cold-blooded). Forecasts from the model were shared with growers via the *VegEdge* web page. This information is critical for understanding BMSB risk as a concern for many late-season high-value crops (sweet corn, tomatoes, raspberries, apples, wine grapes). Moreover, we found that the MN-acclimated BMSB has a faster developmental rate (egg to adult) and females produce nearly 30-40% more eggs/female than previously suspected. Finally, the BMSB development data have been combined with future weather models, summarized by Dr. Peter Snyder's team (Soil, Water & Climate, UMN), to assess potential BMSB change over time.

Project Results Use and Dissemination
A diversity of outreach and dissemination methods were used to deliver research results from this project to a variety of audiences, including farmers of field crops and fruits and vegetables, crop consultants, the general public, and to researchers at professional conferences.

A front page article was published in the Star Tribune about our work, as well as another Star Tribune article the year before. We created a BMSB web resource and fact sheet, which was published in three additional languages: Hmong, Somali, and Spanish. More website resources were created including Degree-day Model forecasts for Midwest Insects: BMSB (updated daily during growing season) and BMSB in MN Apple Orchards and Varietal Impacts. Pieces on our work were published in the University of Minnesota Extension Fruit and

Vegetable News, University of Minnesota Extension Minnesota Crop News in 2016 and 2018, Fruit Growers News, Vegetable Growers News, and a map was created by the Minnesota Department of Agriculture using data from the MITPPC project.

Many peer reviewed publications resulted from this work including in Insects and the Journal of Economic Entomology. Multiple conference presentations were given at places such as Upper Midwest Invasive Species – North American Invasive Species Management Association Joint Conference, Meeting of Entomological Society of America, and the Fifth Biennial Upper Midwest Invasive Species Conference.

ML 2014, Chapter 312, Article 12, Section 8 Project Abstract
For the Period Ending June 30, 2019

PROJECT TITLE: MITPPC Sub-project #3 Climate change and range expansion of invasive plants
PROJECT MANAGER: D. A. Moeller
AFFILIATION: UMN – Twin Cities, College of Biological Sciences, Dept. of Plant and Microbial Biology
MAILING ADDRESS: 1479 Gortner Ave, 140 Gortner Laboratory
CITY/STATE/ZIP: St. Paul, MN 55108
PHONE:
E-MAIL: moeller@umn.edu
WEBSITE: https://moellerlab.wordpress.com/
FUNDING SOURCE: Environment and Natural Resources Trust Fund
LEGAL CITATION: M.L. 2014, Chapter 312, Article 12, Section 8

APPROPRIATION AMOUNT: $206,335
AMOUNT SPENT: $206,335
AMOUNT REMAINING: $0

Sound bite of Project Outcomes and Results

This project provided maps to describe the climate suitability and invasion risk for ten invasive species in Minnesota now and in the future. These findings can be used to guide management decisions about surveillance and eradication efforts for these species.

Overall Project Outcome and Results

In our project, 'Climate change and range expansion', our goal was to use public records of species presences and available environmental data to build models that predicted the habitat suitability and invasion risk under current and future climate scenarios for 10 invasive species of interest to MN. Those species were: Common Tansy, Wild Parsnip, Palmer Amaranth, Oriental Bittersweet, Narrowleaf Bittercress, Japanese Hops, Common Teasel, Dalmatian Toadflax, Brown Knapweed, and Black Swallowwort. We originally planned to include Grecian Foxglove, but were unable to obtain enough data to build reliable models. We developed species distribution models (SDMs) using multiple techniques (Maxent, Boosted Regression Trees, and Joint Distribution Modeling of Communities) and multiple scales (North American continent and Upper Midwest) to validate results. We wrote a report with detailed finding from our SDMs titled, "Species Distribution Model Projections for Incipient Invasive Species of Minnesota". Our findings can be used to help guide management decisions about surveillance and eradication efforts for these species. Additionally, we have published on our findings on methods for producing accurate models of invasive species and specific SDMs for the species of interest in academic peer-reviewed journals. We have also presented our work at the UMISC-NAISMA and Palmer Amaranth Conferences and have participated as presenters in USFS land manager training. The project supported or trained one postdoctoral scholar, one postgraduate research assistant, two undergraduate students, and one graduate student. One undergraduate student decided to continue as a graduate student working on invasive species and is an author on all of the manuscripts and data products. The management document and all of the underlying data, models, and projections are archived at the Data Repository for U of M (DRUM) and are freely available to Minnesotans to access to gain a better picture of the potential distributions of the listed species.

Project Results Use and Dissemination

Our project has resulted in four publications, five major presentations to disseminate our findings at national and regional meetings, and 80 data products that can be accessed by all Minnesotans and natural resource professionals. We have published our SDM results for Palmer amaranth in the open-access journal *Scientific Reports*, which is freely available to the public. We have presented the result of this paper at the UMISC-NAISMA Joint Conference in Oct 2018 in the Palmer amaranth session to scientists and professionals interested in the problem of rapid, invasive spread of Palmer amaranth. We also presented to work as a poster at the first MITPPC Palmer Amaranth Summit in Jan 2019 and Dr. Briscoe Runquist participated in the conference management working groups as scientific expert on the biology and potential for spread of the species. We have also presented this work to the MN NWAC Management and Policy Subcommittee. Additionally, we provided training to US Forest Service professionals about the underlying mechanics of species distribution models and how and when they can be used to effectively forecast and manage the spread of invasive species under current and future climate conditions. Lastly, we produced a document specific to predicted habitat suitability in MN to be used by MN natural resource professionals for surveillance and eradication decision-making. This document will be housed with the MITPPC in hard copy form and will be accessible as a pdf on their website for download.

During the course of this project, we have generated 80 multi-layered data products that have been archived at the Data Repository for U of M (DRUM) with DOI numbers that can be used to quickly access the data. These data products can be used for further analyses for researchers and natural resource professionals. For each of the species, we have collated a list of occurrence records (current through 2018) that are sourced from multiple databases and have been cleaned for problematic records. They are ready for use in multiple applications that require verified occurrence data. We have also generated multiple SDMs, their validation metrics, and current and future projections based on these models for all ten species. We have provided the models and the raster projections for these SDMs as downloadable files. Further, for 3 species, Narrowleaf Bittercress, Oriental Bittersweet, and Japanese Hops, we developed Joint Species Distribution models (JSDMs) to compare with traditional SDMs using DNR relevé data, environmental data, and a Bayesian method for joint attribute modeling. The input data (climate data, species co-occurrence matrices) and output data (models and projections) are also available for use. These models provide data on projections for the invasive species, as well as for other potential plant community members of interest.

SCIENTIFIC REPORTS

OPEN

Species distribution models throughout the invasion history of Palmer amaranth predict regions at risk of future invasion and reveal challenges with modeling rapidly shifting geographic ranges

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Ryan D. Briscoe Runquist, Thomas Lake, Peter Tiffin & David A. Moeller

Palmer amaranth (*Amaranthus palmeri*) is an annual plant native to the desert Southwest of the United States and Mexico and has become invasive and caused large economic losses across much of the United States. In order to examine the temporal and spatial dynamics of past invasion, and to predict future invasion, we developed a broad array of species distribution models (SDMs). In particular, we constructed sequential SDMs throughout the invasion history and asked how well those predicted future invasion (1970 to present). We showed that invasion occurred from a restricted set of environments in the native range to a diverse set in the invaded range. Spatial autocorrelation analyses indicated that rapid range expansion was facilitated by stochastic, long-distance dispersal events. Regardless of SDM approach, all SDMs built using datasets from early in the invasion (1970–2010) performed poorly and failed to predict most of the current invaded range. Together, these results suggest that climate is unlikely to have influenced early stages of range expansion. SDMs that incorporated data from the most recent sampling (2011–2017) performed considerably better, predicted high suitability in regions that have recently become invaded, and identified mean annual temperature as a key factor limiting northward range expansion. Under future climates, models predicted both further northward range expansion and significantly increased suitability across large portions of the U.S. Overall, our results indicate significant challenges for SDMs of invasive species far from climate equilibrium. However, our models based on recent data make more robust predictions for northward range expansion of *A. palmeri* with climate change.

Invasive species are marked by rapid range expansion and dramatic population growth that negatively affects communities and ecosystems outside of their historical range[1]. Because invasive species often cause considerable economic losses, land managers and conservation scientists are in need of tools to forecast invasion risk so that they can direct resources for prevention strategies and targeted surveillance operations[2–6]. Species distribution models (SDM) use species occurrence records and environmental data to build correlative models of habitat suitability and identify key environmental variables limiting range expansion[7–10]. For invasive species, SDMs can be a useful tool for identifying potential habitat requirements and environmental limitations of future range expansion[6,9,11,12]. Further, the models provide testable hypotheses that can be evaluated with field experiments and long-term observation of population dynamics. However, because invasive species often violate key assumptions of SDMs, we do not fully understand the extent to which they are reliable for predicting potential invasive species' range expansion[9,13]. In this study, we leveraged detailed historical records for the rapid invasion of Palmer amaranth (*Amaranthus palmeri*) to assess if and how SDMs predict the explosive range expansion during the invasion process. Because *A. palmeri* is among the most problematic emerging threats to natural (e.g. prairies, grasslands)

University of Minnesota, Department of Plant and Microbial Biology, 1479 Gortner Avenue, St. Paul, 55108, MN, USA. Correspondence and requests for materials should be addressed to R.D.B.R. (email: rbriscoe@umn.edu)

and agricultural ecosystems in the United States, accurate SDMs may be particularly valuable for preventing and mitigating future invasion.

Developing SDMs for invasive species can be considerably more challenging than for native species. SDMs operate under the assumption that a species is at equilibrium with the environment and that there are not large areas that are suitable but unoccupied; however, invasive species are, by definition, not at equilibrium[9]. SDM methods have been adapted to ameliorate some of the inherent problems of invasive species modelling but these methods can have differing effects on invasion projections and interpretation. For example, because environments (and correlations among environmental variables) may differ outside of the range compared to inside, modelers may retain more environmental variables to capture this variation[9,14]. In addition, it is unclear whether models built using invaders' native ranges improve or hinder predictions of future range expansion[6,15–17]. Developing SDMs for invasive species can be especially problematic in cases where adaptation and/or admixture influence niche breadth over the course of invasion history[17–19]. In these cases, the genetic composition of populations, and thus the environmental factors that determine reproductive success, may differ between the native and invaded ranges. As a result, both ecological (dispersal limitation) and evolutionary factors (gene flow, adaptation) violate key assumptions of SDMs.

Although invaders often arrive from other continents[1,20], they can also emerge within a single continent and exhibit rapid range expansion[21–24]. Similar to trans-continental invaders, within-continent invaders often exhibit explosive demographic expansions and can cause similarly disruptive ecosystem effects[22–24]. At the same time, these invaders may possess a unique subset of characteristics (e.g. association with anthropogenic change) and management challenges that are vital to document and model in order to develop effective management strategies[1,23,24]. Modelling within-continent invaders offers the opportunity to study how SDMs perform when an invasion occurs directly from a native range to adjacent ecosystems and across continuous environmental gradients. Investigations of native invasion can more readily distinguish among the alternative causes of sudden range expansion including climate, biotic interactions (e.g. competitive environment), or dispersal limitation[22–24].

Amaranthus palmeri is an annual, dioecious plant with a relatively narrow native range that includes the desert Southwest of the United States (especially Arizona and New Mexico) and northwest Mexico (Sonora)[25]. Beginning in the mid 20th century, its range rapidly expanded north and east with populations now found throughout most of the continental United States, except for New England, the Rocky Mountain region, and Pacific Northwest[25–27]. In the last two decades, *A. palmeri* has become one of the most economically-damaging weeds in the United States[28,29]. Invasion has occurred most commonly into restorations of natural habitat (i.e. conservation plantings) and agricultural fields via contaminated seed sources and agricultural equipment, respectively[28,30]. Crop yields in fields infested with *A. palmeri* may be reduced by more than half[31,32] and yield losses have the potential to reach as high as four billion dollars annually in the mid-South alone[33]. Despite the enormous economic impact and continued range expansion, the environmental controls of its distribution and predictions for its future spread remain poorly resolved.

In this study, we examined the range expansion dynamics of *A. palmeri* from its historical to current range and used SDMs to predict the distribution of suitable habitat across North America throughout the invasion process and under future climates. To determine whether SDMs would have been successful if implemented at early versus late stages of the invasion, we took advantage of the detailed record of invasion and abundant occurrence dataset to construct SDMs at five time points in the invasion process. Because rapidly-expanding invasive species can be challenging to model, we used a broad array of modeling approaches (native + invaded range vs. invaded range only, Maxent vs. boosted regression trees, alternative climate datasets, downsampling overreported areas, etc.) to determine their consequences for model accuracy and discrimination ability under both current and future climates. We also determined which environmental factors most influenced projected habitat suitability and potentially limit range expansion into unoccupied regions. Finally, we examined the contribution of stochastic long-distance dispersal to range expansion using spatial autocorrelation analyses.

Results

Niche breadth and overlap between the native versus invaded ranges. We characterized the climate niche breadth of *A. palmeri* and quantified the extent to which the climate niche has shifted and/or expanded in the invaded range. We used an approach that first involves principal components analysis (Fig. S1) and then accounts for the frequency of occurrence records in environmental space and the frequency of environments[34].

The invaded range represented both a niche shift (change in centroid) and niche expansion (increase in extent) based on principal components of both CliMond (Fig. 1) and PRISM climate data (Fig. S2). This niche shift and expansion was also apparent along individual environmental variable axes (Fig. S3). Further, niche shift and expansion were evident from niche similarly tests[34], which indicated that in the invaded range, the environments in which *A. palmeri* occurs are not more similar to the native range environments than random; although for CliMond the result was near significance ($p = 0.064$ and $p = 0.196$; CliMond and PRISM respectively). Despite a niche shift, there remains considerable overlap between the native and invaded range niches ($D = 0.32$ and 0.28 for CliMond and PRISM respectively; Figs 1, S2, S3).

SDMs generated from all occurrences in the native and invaded range. To generate SDMs, we obtained records from publicly available sources (GBIF and EDDMaps) and land manager records (see Methods for details) and filtered records to remove duplicates or errors. Within the filtered dataset, occurrence points were unevenly distributed because of variation in natural occurrences and sampling biases. We downsampled the dataset to a 50 km grid to minimize the disparity in sampling density among geographic areas (hereafter: native + invaded dataset). We explored SDMs built using Maxent and Boosted Regression Trees (BRT: see the electronic supplementary materials for BRT results).

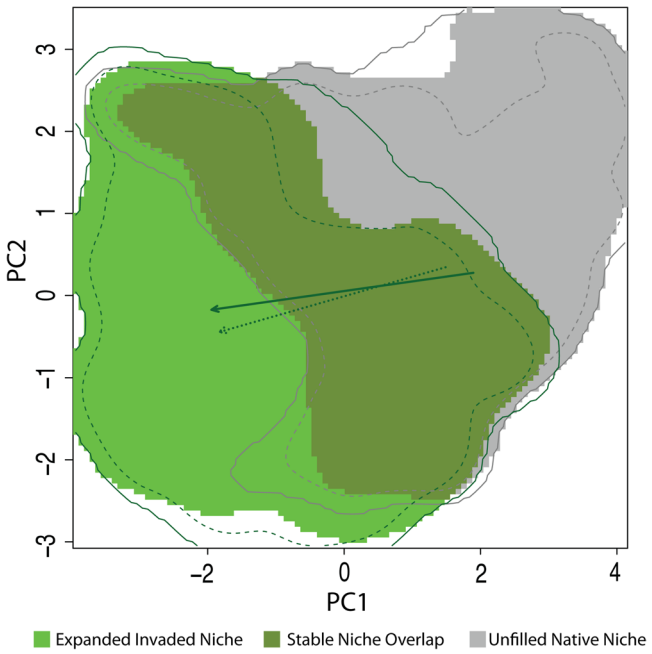

Figure 1. Niche breadth and shift of native versus invaded niche. Axes are principal components of CliMond variables included in the model. The total extent of the background environment in the native region is outlined in grey (solid = total niche space; dashed = 90% of extent). The total extent of the background environment in the invaded region is outlined in dark green (solid = total niche space; dashed = 90% of extent). The environmental space unique to the native niche is shown in gray (9.1% weighted loss of the original niche), the area of environmental space shared between the native and invaded niche is shown in olive-green (87% of the total weighted invaded niche), and the region of environmental space newly occupied by the invaded niche is shown in green (i.e. niche expansion; 13% if the total weighted invaded niche). The arrows represent the shift in the weighted centroid of occurrences from native to invaded niche (dark solid arrow), and the shift in the center of environmental space (lighter dashed arrow). The weighted niche overlap, calculated using Schoener's *D*, was 0.32.

Species distribution models (SDMs) built with the native + invaded dataset indicated that a large portion of the conterminous United States and northern Mexico have high predicted probabilities of occurrence. For both the CliMond (projections in blue/green color palette) and the PRISM (projections shown in pink/purple color palette) models, areas of highest probability of occurrence included large portions of the desert Southwest, the Central Valley of California, most of the Midwest, the Southeast, the Mid-Atlantic, and southern New England (Fig. 2A,C). Areas predicted to have low probability of occurrence included mountainous regions and the highest northern latitudes of the United States (Fig. 2A,C). The SDMs based on PRISM data, which are centered on 1995 (compared to CliMond data, which is centered on 1975), showed higher predicted probabilities of occurrence at higher latitudes, with urban areas in the northern parts of the range having slightly higher probabilities of occurrence than surrounding rural areas (Fig. 2C).

Both CliMond and PRISM models had high predicted probabilities in a number of areas that are currently either unoccupied (e.g. the Palouse) or potentially unreported (e.g. Alabama, the Mid-Atlantic region, Ohio). Many of these areas report the presence of the species in the state but do not provide georeferenced occurrences and thus were not used to train our models (e.g. Maryland, Pennsylvania, New York; Fig. 2A,C). By contrast, the models predicted that recently colonized areas at the northern range margin (e.g. Minnesota, Wisconsin, Michigan) had marginal habitat suitability.

Both CliMond and PRISM models had low discrimination (AUC scores: 0.56–0.62), but moderately high model accuracy (TSS scores: 0.69–0.70; Table S1). Models performed similarly or marginally better in the native range than invaded range by most metrics (CliMond: Native-AUC: 0.67 v. Invaded-AUC: 0.61, Native-TSS: 0.53 v. Invaded-TSS: 0.49; PRISM: Native-AUC: 0.63 v. Invaded-AUC: 0.63, Native-TSS: 0.23 v. Invaded-TSS: 0.51).

For CliMond models, average annual temperature and radiation seasonality had the greatest variable contributions, 47.4% and 24.4% respectively (Table 1). For PRISM models, average minimum and maximum temperatures had the greatest variable contributions, 34% and 33% respectively (Table 1). The probability of occurrence along the northern range margin and in the Mountain West was most limited by low temperature (mean annual temperature for CliMond and low mean minimum temperature for PRISM; Fig. 3A,C). The probability of occurrence in the Southeast was most limited by high precipitation (CliMond and PRISM) and high vapor pressure (PRISM).

Including land cover in the models modestly increased model performance as measured by AUC (0.63–0.66) but not TSS (0.60–0.61; Table S1) and increased the predicted probability of occurrence in urban centers, particularly in northern regions (Electronic supplementary material, Fig. S4). Land cover also had a high relative variable contribution (60% for CliMond models, 57% for PRISM models; Table 1).

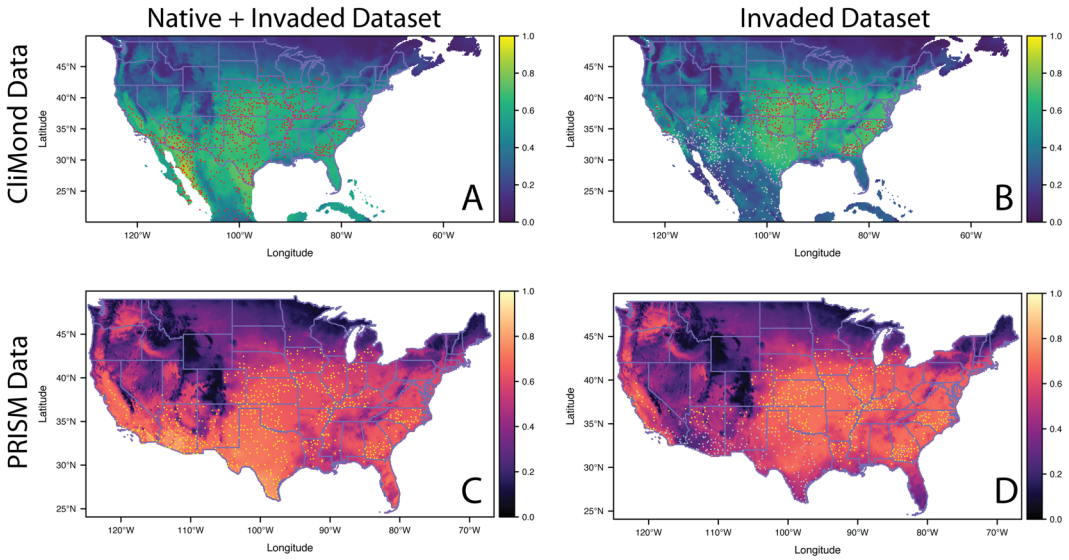

Figure 2. SDM model projections of *Amaranthus palmeri* generated using CliMond and PRISM variables for the native + invaded dataset and invasive only dataset. All projections are means of 25 model runs. Panels A and B were generated using CliMond environmental variables (blue/green color palette) and panels C and D were generated using PRISM variables (pink/purple color palette). Panels A and C used the native + invaded dataset for model building and panels B and D used the invasive only dataset. In panels A and B the occurrences included in the model are shown in red and in panels C and D the occurrences included in the model are shown in yellow. All other occurrences are in gray. The complementary log-log predicted probability for each raster cell is indicated by the color corresponding the bars to the right of the panels.

		Native + invaded Dataset				Invaded Dataset	
		Climate Only		Climate + Land Cover		Climate Only	
Variable	Bioclim #	Mean	SE	Mean	SE	Mean	SE
CliMond Environmental Variables							
Mean annual temperature	Bio 1	47.38	2.95	18.97	1.79	40.19	2.62
Mean diurnal temperature range	Bio 2	3.45	0.6	0.92	0.22	8.98	1.24
Annual precipitation	Bio 12	3.52	0.66	2.14	0.43	19.92	3.23
Precipitation seasonality	Bio 15	4.16	0.75	3.00	0.37	2.19	0.48
Radiation seasonality	Bio 23	24.46	2.17	7.91	0.97	11.11	2.00
Annual mean moisture index	Bio28	10.32	1.49	5.74	0.81	5.56	1.14
Moisture index seasonality	Bio31	6.71	1.36	1.72	0.4	12.04	1.62
Land Cover	—	—	—	59.6	1.54	—	—
PRISM Environmental Variables							
Maximum temperature	—	33.37	4.05	16.17	1.89	14.34	3.49
Minimum temperature	—	34.72	3.95	15.31	2.16	36.25	4.83
Precipitation	—	6.93	1.10	2.66	0.44	10.89	1.87
Maximum vapor pressure deficiency	—	6.00	1.35	3.45	0.83	2.99	0.85
Minimum vapor pressure deficiency	—	13.5	1.58	4.60	0.84	11.13	1.71
Dew Point	—	5.48	1.36	1.13	0.64	24.4	4.77
Land Cover	—	—	—	56.69	1.48	—	—

Table 1. Mean and standard errors of relative contributions of environmental variables included in Maxent models. Models were built using climate variables from CliMond or PRISM. Models were built with occurrences from either the native + invaded dataset or the invaded dataset. For the native + invaded dataset, models included either climate variables only or climate variables plus land cover. All metrics are based on the averages of 25 model runs (see methods).

SDMs generated only from occurrences in the invaded range. It is not clear if SDMs of invasive species perform better when generated from the entire range or the invaded range[6,15,16,19], therefore we also built SDMs with occurrence records from only the invaded range. Similar to models built with native + invaded occurrences, these models predicted high suitability in most of the invaded range (i.e. central and southeastern United

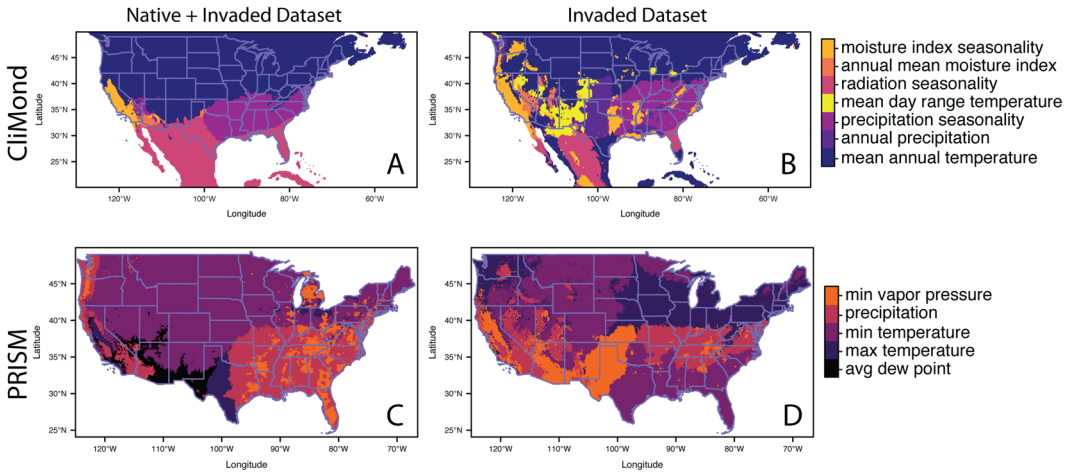

Figure 3. Limiting environmental factors on predicted probability for *A. palmeri*. The map depicts which environmental factor in the Maxent models contributes most negatively to the predicted probability of occurrence in each raster cell. The panels mirror the maps in the previous figure. Panels A and B are CliMond variables, panels C and D are PRISM variables, panels A and C are for models built with the native + invaded dataset and panels B and D are for models built with the invasive only dataset. Maps show are representative of the limiting factors by geographic region for the 25 models in the results.

States); however, they performed comparatively worse in predicting occurrences in the native range (Fig. 2B,D). By contrast, the invaded range models were more successful in predicting occurrences at the northern range margin (Fig. 2B,D).

Similar to models based on data from the native + invaded range, models based on only the invaded range (both CliMond and PRISM) had low discrimination ability (AUC: 0.60–0.64; Table S1) and moderate accuracy (TSS: 0.64–0.68; Table S1). The most important environmental variables were mean annual temperature (40%) and mean annual precipitation (20%) for CliMond, and mean minimum temperature (36%) and dew point (24%) for PRISM (Table 1). The highest contributing variables for both climate datasets were the same as for the native + invaded model.

As with the native + invaded range model, low temperature was limiting for habitat suitability at the northern range margin. However, the invaded range models also indicated that a broad temperature range limited suitability at the northern range limit (Fig. 3B,D).

Range expansion dynamics. The number of occurrence records and geographic range increased dramatically after 1950 (95% of records since 1950), when *A. palmeri* was first reported to spread outside of its native range and >50% of records are from the last 10 years (Fig. 4I).

An increasing pace of invasion was also evident in the change in area of occupancy through time (area of occupied grid cells; Fig. 4J). The relationship was linear until approximately 2000–2010 (linear AICc: 76.1; log-linear AICc: 76.7); however, since 2010, an accelerating (log-linear) relationship provided a better fit (linear AICc: 97.2; log-linear AICc: 89.8).

Models built using data from 2010 and before did not forecast the extent of the current invaded range (Fig. 4A–H; model evaluations in Table S2). In the modelled range, sequential historical models had low overall discrimination (AUC: 0.58–0.63) and moderate accuracy (TSS: 0.62–0.74). Additionally, historical models were not able to predict future occurrences better than random, even when evaluations were limited to regions with only analogous climates (AUC: 0.53–0.55, TSS: −0.12–0.16). When projecting habitat suitability across North America, the proportion of suitable habitat only increased modestly from ~20% (1970) to 25–30% (1980 to 2010), then abruptly increased to ~50% in 2017 (Fig. 4K).

Occurrences in the native range were spatially autocorrelated at all three spatial scales assessed (1 and 10 nearest neighbors, all neighbors within 10 km: Join-count pseudo $P < 0.0001$). By contrast, in the invaded range, occurrences were spatially autocorrelated only at the larger spatial scales ($P < 0.0001$ for both 10 nearest neighbors and all neighbors within 10 km, $P = 0.74$ for single nearest neighbor). The weaker autocorrelation at the finest spatial scale suggests that stochastic long-distance dispersal events likely contributed to the invasion process rather than wave-like spread from nearest neighbors, alone.

Projected future distributions. Under all future climates, using the native + invaded range models, the area of high habitat suitability expanded and models projected greater habitat suitability in the Upper Midwest (MI, WI, MN, ND, SD), Pennsylvania and New York. Projections of the invaded range models predicted a similar northern expansion of suitable habitat, albeit accelerated and more extensive. For example, regions of high suitability are evident in central Minnesota and North Dakota by 2030, and by 2070 the majority of both states are deemed highly suitable (Figs 5A–D, S5–S7).

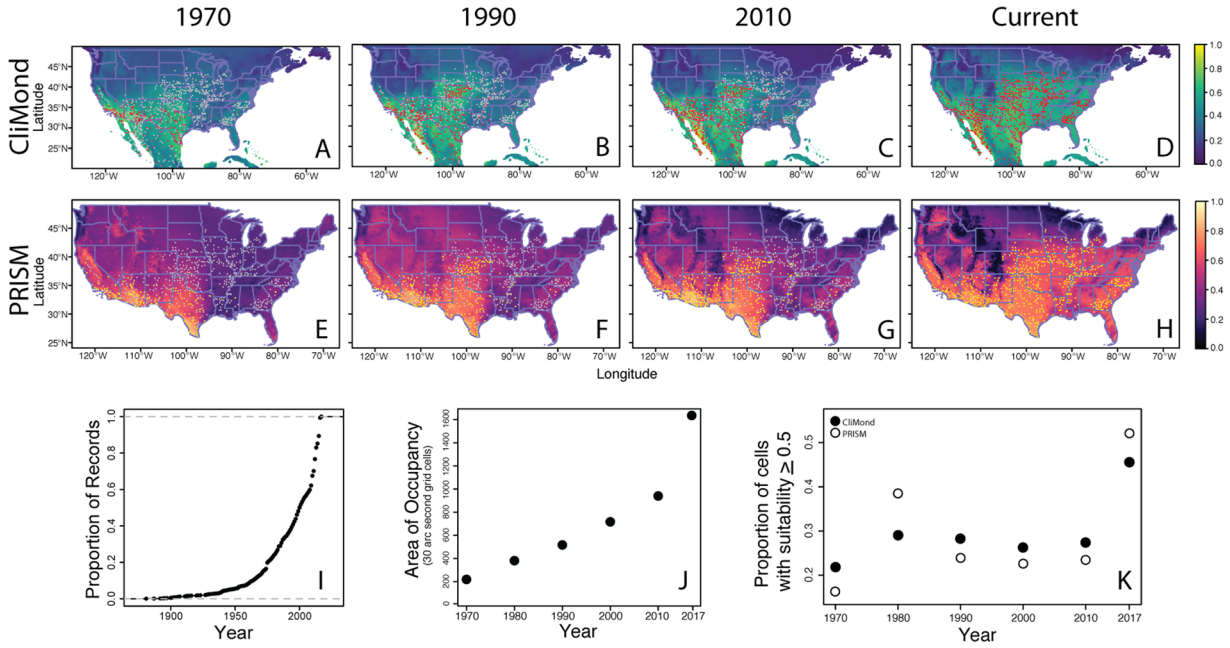

Figure 4. Sequential historical models and time series analyses of *A. palmeri*. Panels depict models built with occurrence records that include data up to a given year (1970, 1990, 2010). Projections on the top row (panels A–D) were built with CliMond environmental variables and those on the second row (panels E–H) were built with PRISM environmental variables. Occurrence records used to build models are in red (A–D; CliMond) or yellow (E–H; PRISM) all other occurrences are in gray. The complementary log-log predicted probability for each raster cell is indicated by the color corresponding the bars to the right of the panels. Metrics of range expansion are on the bottom row. The panel I depicts the accumulation of records through time. The panel J depicts the change in Area of Occupancy (measured in number of 30 arcsecond grid cells) over time. Lastly, the panel K depicts the average predicted probability over all grid cells for models built at each time period.

Discussion

Species distribution models based on current records of occurrence accurately predicted *A. palmeri's* invaded range and indicated that temperature plays a particularly important role in limiting habitat suitability at the northern range margin. SDMs performed better when we used occurrences only from the invaded range, rather than including the native range as well. Under future climate scenarios, our models predicted northward range expansion and increased suitability in regions that are already occupied but of moderate suitability (e.g. upper Midwest). Unfortunately, SDMs performed quite poorly when we attempted to predict the current invaded range from earlier phases of the invasion history (e.g. occurrences until 1970, 1980, 1990, 2000, 2010). Analyses of invasion dynamics suggest that stochastic movements across the landscape have contributed importantly to rapid range expansion, rather than a wave-like spread, alone. Our models make robust predictions about incremental expansion in the future but suggest caution when employing SDMs to predict the potential geographic range of invasive species that are far from equilibrium with the environment.

We used a diverse set of modelling approaches and all of them had modest discrimination ability. This was evident by low AUC scores (but TSS indicated moderate to high accuracy), weak signal in individual environmental variables, and predictions of low habitat suitability in currently occupied regions at the range margin. Discrimination ability and predictions of habitat suitability were consistent across all versions of our models, suggesting that the modelling approach was not the likely cause. Instead, the climate datasets along with the biology and invasion history of *A. palmeri*, may have contributed to limited SDM discrimination. First, the climate datasets used (CliMond and PRISM) are constructed based on mean data over a 30-year timeframe (CliMond: 1961–1990; PRISM: 1970–2010). Therefore, it is possible that our models are conservative with respect to predictions of habitat suitability, and occurrences along the range margin, particularly in the north, may reflect recent warmer than average years. Second, it is possible that climate has not been the main driver of distributional limits but rather that they have been caused by other factors (e.g. dispersal or biotic interactions). For example, range expansion may have been limited by the availability of disturbed, low-competition habitats[35,36] that have become more common in the past 70+ years with industrialized agriculture[37]. Third, annual plants such as *A. palmeri* can often exploit a broad range of climates by exploiting only the fraction of the year that is suitable via altered timing of germination and reproduction (i.e. niche construction[38]). Last, populations may have adapted to novel environments during range expansion, which has resulted in a broad set of suitable climates across the species' range and a weakened signal of individual environmental variables in SDM construction. Together, these historical and biological factors may contribute to modest model discrimination/accuracy but also provide important insight for future work on the causes of distributional limits. We consider each of these issues in detail below.

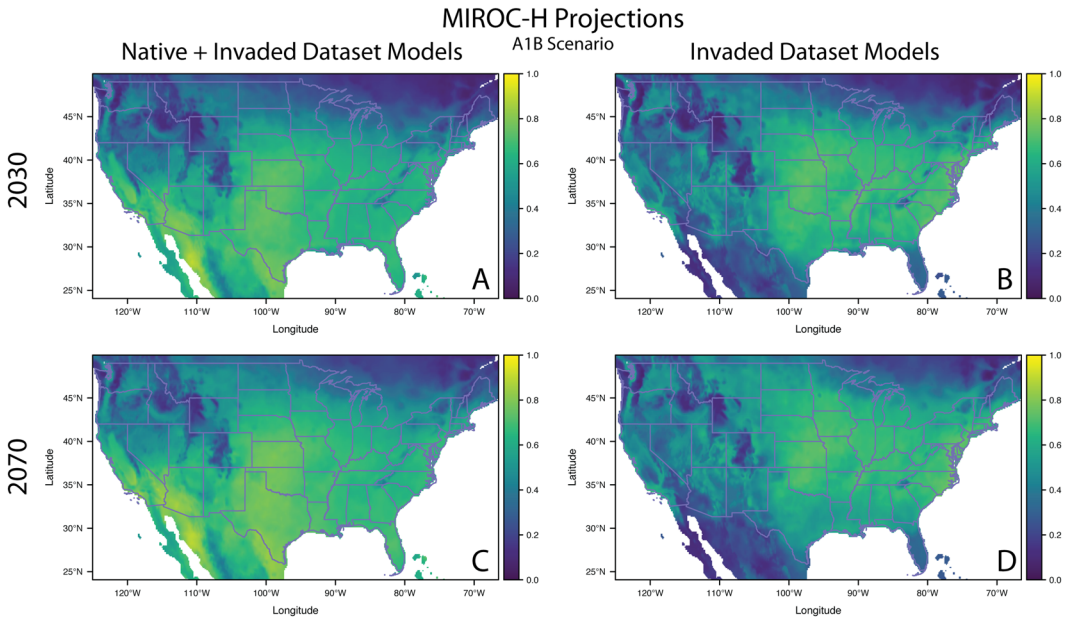

Figure 5. Model projection of *A. palmeri* under future climate change scenarios. The projections are for the MIROC-H Global Circulation Model under the A1B emissions scenario. Panels A and B are based on projected environmental variables in the year 2030 and panels C and D for year 2070. The panels A and C are projections based on models built with the native + invaded dataset and panels B and D are based on models built with the invasive only dataset. The complementary log-log predicted probability for each raster cell is indicated by the color corresponding the bars to the right of the panels.

Amaranthus palmeri remained within the bounds of its native range until the middle of the twentieth century but quickly began to spread by the 1970s and 1980s[28]. We took advantage of the detailed time series of occurrence data to ask how SDMs performed at sequential stages of the invasion process. Models built with occurrence records until 1970, which were primarily from the native range and early invasion, predicted very little of the extent of the eventual invaded range. Models built using occurrence records until 1980, 1990, and 2000 also performed poorly in forecasting the eventual invaded range. Qualitative inspection of projections indicate that models were successful in predicting the invasion of geographic regions immediately adjacent to the occupied range (i.e. short periods into the future) but failed to predict over broader geographic areas (and longer time scales). These results imply that climate was not an important factor in the early stages of the invasion and that dispersal limitation contributed to limits on range expansion. Our models that incorporated land cover made similar predictions about the extent of invasion, but also emphasized that human disturbance was likely an important factor in range expansion. Similarly, a meta-analysis by Simberloff *et al.*[24] found that most invasions of native plants are not limited by climatic variables and instead are associated with anthropogenic change, such as alteration of grazing and fire regimes. The association of *A. palmeri* with natural and human-caused disturbed habitats may in part explain the original restriction and current movement of the species.

Our results also suggested that stochastic long-distance dispersal contributed to rapid range expansion throughout the invasion process. The total area of occupancy for *A. palmeri* in North America increased linearly during most of the invasion history but began to accelerate rapidly approximately in the last decade (2010–2017). We also found that occurrences in the invaded range were not spatially-autocorrelated at fine spatial scales (nearest neighbors) indicating that stochastic movement (e.g. long-distance dispersal events) has likely been important. This result is consistent with observations from other systems, and theoretical models, which have suggested that rapidly expanding ranges often spread via short-distance dispersal at range margins coupled with rare long-distance stochastic dispersal[39,40]. Such rapid and stochastic invasion is most likely to occur when an invader is far from equilibrium with the environment (e.g. climate), with large amounts of suitable but unoccupied territory.

Although we detected a recent acceleration in invasion speed and stochastic spread, our models suggest that *A. palmeri* is closer to reaching the boundaries of its potential range. Models built with the most recent datasets (2017) best predicted large geographic areas that have recently been invaded but do not have occurrences included in model building (e.g. Maryland, Pennsylvania, New York, and portions of the Southeast and Upper Midwest; USDA Plant Database; https://plants.usda.gov); whereas, models built with older datasets underpredicted areas at risk for future invasion. Similar to our results, Václavík and Meentemeyer[41] found that early in the invasion history of *Phytophthora ramorum*, models underpredicted areas at risk for future invasions, but that late in the invasion more models readily predicted unoccupied areas that were later invaded. Therefore, our models based on current datasets may likely make more robust predictions about future invasion than those based on data from earlier in the invasion process.

One of the difficult decisions faced by modellers of invasive species is whether and how to use occurrence information from the native range in modelling and projecting invasive ranges[6]. In many cases, using native plus invasive records overpredicts habitat suitability in unoccupied areas[12]; whereas, using only the invaded range better predicts potentially suitable unoccupied areas. In our models, we found that using occurrences from the native + invaded range underpredicted some areas that have already been invaded (i.e. the Midwest, Southeast, and Mid-Atlantic; Figs 2A,C, S8). These newly-invaded regions had higher predicted habitat suitability when models were built using data from only the invaded range. Therefore, like many other invasive species, newly-invaded areas are best predicted by models built only with invaded occurrences[6,19]. This is likely because the native range is a narrow subset of climates compared to the invaded range. Indeed, our niche analyses showed that the native and invaded ranges occupied different, but overlapping, climatic niche space, which is common for many invasive species[19,42]. This niche shift makes it potentially problematic to model invaded regions using native-only models or models where a high density of native occurrences might heavily bias the SDM.

Range expansion may have been facilitated by adaptation and/or admixture. *Amaranthus palmeri* may have adapted to novel environments (e.g. temperature and precipitation regimes) during northern and eastern range expansion and thus differentiated from native genotypes. Thus far, there is evidence that resistance to glyphosate application quickly evolved[43], which has greatly enabled its spread into agricultural fields[28]. Because SDMs assume that all populations have the same climate niche, local adaptation across the range violates this assumption and may produce biologically unrealistic predictions[7–9]. This may make it more important to build detailed, regionally-informed models to capture patterns of relevant environments and genotypes. In addition to adaptation from standing genetic variation, admixture from closely-related species could also contribute to range expansion and confuse SDMs. Admixture has been documented with *A. tuberculatus*[44,45], a widespread species in the central United States (ranging from Canada to Mexico) but it's importance for adaptation to northern and eastern environments remains unclear. Nevertheless, it is possible that *A. tuberculatus* has served as an important source of adaptive genetic variation during range expansion. Given the potential for evolution to influence invasion dynamics in this system, it would be particularly profitable to build SDMs that incorporate information on functional traits and adaptive differentiation[46,47].

Methods

Study system. *Amaranthus palmeri* is a dioecious, wind-pollinated, obligate outcrossing, annual plant that harbors substantial genetic diversity within and among populations[26,28,31,45]. In its native range, *A. palmeri* occurs in dry, itinerant stream and riverbeds and other habitats subject to frequent disturbance[25,26,28]. *A. palmeri* has high photosynthetic rates, grows rapidly, and can quickly deplete soils of nutrients[48–50]. Its seeds can germinate throughout the growing season and plants can successfully reproduce at almost any size or age[26,28]. This combination of traits has predisposed the species for success in agricultural fields and other disturbed areas[26]. There is also evidence for widespread herbicide resistance (e.g. glyphosate) and other adaptations to weed control, including delayed germination and rapid development[28].

Species occurrence records. *Data sources.* We gathered 3,967 occurrence records, ranging in dates from 1896–2017, from open-access databases and herbarium networks including: Global Biodiversity Information Facility (GBIF; www.gbif.org; Appendix A), Early Detection Distribution Mapping System (EDDMapS; www.eddmaps.org; Appendix A), and the Southwest Environmental Information Network (SEINET; swbiodiversity.org/seinet; Appendix A). We also incorporated 434 county-level occurrence records (approximately the same geographic precision as the minimum for the primary environmental dataset; see below) for several Midwestern and Southeastern states (AK, IA, IL, IN, MI, MO, MN, MS, NE, OH, SD, TN; Appendix A) where few detailed records were available. These data were provided directly by state land managers; exact localities were not provided to protect landowner identity. For these county-level data we used the geometric centroid of each county as the location of occurrence.

Environmental data. To generate SDMs and quantify niche dynamics, we used climate data extracted from CliMond (www.climond.org)[51] and PRISM (prism.oregonstate.edu). From CliMond, which is based primarily on climatological data from 1961–1990, we extracted data for all 35 bioclimatic variables at 10 arc-minute resolution (the finest scale available for all GCMs used). From these 35 variables, we identified seven predictor variables: mean annual temperature, mean diurnal temperature range, annual precipitation, precipitation seasonality, radiation seasonality, mean annual moisture index, and moisture index seasonality. We selected these variables because they were not strongly correlated (Pearson $r < 0.8$) and described the major axes of climatic variation along the first two axes of a PCA of the current range. We also extracted seven climate variables, including one composite variable, from PRISM, which is based on data collected from 1981 to 2010 at 30 arc-second resolution. For PRISM, we retained all variables except mean annual temperature, which was highly correlated with minimum and maximum temperature. We retained more variables than is typical for many SDMs to provide more robust predictions of habitat suitability in unoccupied regions and under future climate projections[14]. For a subset of SDMs, we included the land cover layer as an additional categorical variable. We obtained data on land cover (2011 land cover characterizations, www.mrlc.gov/nlcd11_data.php) from the Multi-Resolution Land Characteristics Consortium (www.mrlc.gov/) and rasterized the image to an 800 m resolution using the R 'raster' package[52,53].

Tests of niche differentiation. We tested for niche differentiation between the native and invaded range following Broennimann *et al.*[34] using the 'ecospat' package in R[54]. Using climate data from CliMond and PRISM, we calculated the extent of the native and invaded niche (niche breadth) and the native and invaded niche centroid, which was weighted by the number of occurrences and the availability of the environment. We defined total

niche space using principal components analysis (PCA-env[34]) for the 100 km background buffers used for building SDMs (i.e. see 'SDMs for the native + invaded range and invaded range only' section below). We quantified niche overlap using Schoener's *D*, which varies between 0 and 1 (zero and complete niche overlap, respectively). We tested if the invaded niche was more similar to the native niche than expected by chance using a permutation test (N = 999 permutations) for niche similarity (i.e. are invaded occurrences in the invaded range more similar to the native niche than expected by chance)[34]. We also characterized the niche breadth and overlap along individual environmental axes (Electronic Supplementary Materials).

Data preparation for SDMs. We manipulated and analysed spatial data in the R environment version 3.4.1[52] using the geospatial data abstraction library (GDAL) implemented in package 'rgdal' and the Geometry Engine Open Source (GEOS) implemented in the package 'rgeos'[55]. To manipulate spatial point data, we used the 'sp' package[55–57].

Prior to analyses, we removed all records that were geographic outliers, duplications, or had very low coordinate precision (<0.1 decimal degrees, ~10 km precision), which left 1,453 records (hereafter: filtered dataset). Within this filtered dataset, occurrence points were highly unevenly distributed because of variation in natural occurrences and sampling biases. In particular, the species' native range (SW U.S., NW Mexico) was far more heavily sampled than nearly all of the invaded range. To minimize the disparity in sampling density among geographic areas we down-sampled occurrence records to a 50 km grid, resulting in dataset containing 791 occurrences (hereafter: native + invaded dataset). The SDMs we present in this paper were generated using this native + invaded dataset but for comparison, we also performed analyses on the 1,453-record filtered dataset (reported in Electronic supplementary material, Fig. S8).

SDMs for the native + invaded range and invaded range only. We built SDMs using Maxent version 3.4.1[58,59] and Boosted Regression Trees (BRT)[60]. The two approaches produced similar results and we therefore focus on the Maxent models and present BRT methods and results in the Electronic Supplementary Materials. One set of models was built based on the native + invaded occurrences (n = 791) and a second set included only those in the invaded range (n = 427). The invaded range was defined using expert-drawn range maps from before most of the invasion occurred[25]. We used the 'dismo' package[61] to build Maxent models and the 'gbm' package[62] to build boosted regression tree models. We also used the packages 'ROCR'[63] and 'rmaxent'[64] for evaluating models and for generating rapid model projections. We projected models using the 'project' function in the package 'rmaxent'[64]. Last, we visualized all projections using the package 'rasterVis'[65].

For Maxent, we generated background points by selecting points from a polygon object generated by drawing 100-kilometer buffers centered on each presence point and dissolving overlaps. We randomly selected 10,000 points from the polygon while accounting for differences in area of raster cells at higher latitudes[10]. Background points generated this way capture the relevant climatic variation within the area of dispersal[41,66], while balancing the tendency for inflated validation metrics (e.g. AUC) resulting from sampling large areas[67].

We trained the model with 80% of the occurrence and background data and withheld 20% for model validation. Models were built allowing for all feature types[10] and with a regularization parameter of 3 ('betamultiplier'), which had the best performance among models where we varied the regularization parameter from one to five[68]. Finally, we built five models with five-fold cross validation (25 total models) to account for potential variation in model parameters.

We used Multivariate Environmental Similarity Surfaces (MESS) to classify analogous climate regions in North America that were used for two purposes: (1) to identify appropriate unoccupied habitats (e.g. areas under threat of invasion) for model projections and (2) to calculate evaluation metrics for sequential historical models using only relevant future occurrence records (see 'Range expansion dynamics' below). For all models, we calculated MESS based on background points within the 100 km background buffers used for model-building[7,9]. Analogous climate areas were defined as having similarity values greater than 0. For models built with the native + invaded and invaded range datasets, we found that the conterminous United States was deemed as climatically similar enough to be suitable for accurate model projection.

To determine which climatic variables most negatively influenced the probability of occurrence, we generated limiting factor maps using the 'limiting' function in the package 'rmaxent'[64]. This function identifies which bioclimatic variables weigh most negatively on the predicted probability value at each raster cell in a Maxent projection[9,64]. Identifying limiting factors in unoccupied regions can indicate which factors most likely hinder range expansion.

Model evaluation. We evaluated model performance using two statistics: Area Under the Curve (AUC) and True Skill Statistic (TSS). AUC (also referred to as 'ROC') scores evaluate how well a model performs relative to random chance and gauges the model's discrimination ability[69]. We computed two values for AUC: (1) AUC-train, calculated using training data to determine how well the model predicts the data used in model building and (2) AUC-test, calculated using testing data retained for validation to evaluate the ability of the model to predict new information.

We calculated the True Skill Statistic (TSS)[70], which describes the ability of a model to correctly classify presences and background data.

$$\text{TSS} = \text{True Positive Rate (TPR)} + \text{True Negative Rate (TNR)} - 1$$

TSS values range from 1, which is indicative of perfect accuracy (i.e. models predict all presences), to −1, which is indicative of perfect inaccuracy (i.e. models do not correctly predict any presences). TSS = 0 indicates that the model performs no better than random. We evaluated TSS at a model-dependent threshold value, at which the sum of TPR and TNR was maximized (threshold values ranged between 0.5 to 0.65)[71,72].

Range expansion dynamics. To examine the temporal dynamics of invasion we conducted two series of analyses on five data subsets each of which contained all of the records in the native + invaded dataset that had been collected up to the years 1970, 1980, 1990, 2000, and 2010 (n = 146, 235, 309, 390, 458); prior to 1970, there were too few records to build reliable models. First, to characterize the fine-scale rate of spread across North America, we calculated the Area of Occupancy (AOO) as the number of grid cells (30 arcsecond size) with records. We also built SDMs at each time point (same methods as for the datasets described above) to visually compare projections and to quantify the proportion of grid cells with a predicted probability of occurrence $\geq$0.5. We evaluated these models in two ways. First, we calculated evaluation metrics using a testing dataset withheld during model building. Second, we evaluated the models' ability to predict future invasion by calculating evaluation metrics (AUC and TSS) using all future occurrence records found in analogous climate space. For sequential historical models, only subsets of the US contained analogous climates. Therefore, only occurrence records that occurred within those regions were used to calculate evaluation metrics base on future prediction of occurrences.

Second, we examined whether the pattern of range expansion was more consistent with wave-like versus stochastic movement. Wave-like movement causes higher levels of spatial autocorrelation than stochastic movement among occurrences because the bulk of propagule movement is local[73]. We used the filtered dataset (2017) to assess spatial autocorrelation at three spatial scales: single nearest neighbor, ten nearest neighbors, and all neighbors within a 50 km radius. To determine the extent of spatial autocorrelation, we calculated the join-count statistic which tallies the number of links between nearest neighbors (i.e. presence-presence, presence-absence, absence-absence). To determine number of same-type joins that would be expected by chance we generated 999 permuted datasets and calculated the join-count statistic for each. To determine if patterns of spatial autocorrelation were different between native and invaded ranges, we performed analyses separately for each region. We used the 'spdep' package to perform spatial autocorrelation analysis[74,75].

Projected future distributions. To make predictions about potentially suitable future habitats, we obtained the same bioclimatic variables for CliMond from the general circulation models (GCM) CSIRO-Mk3.0 and MIROC-H for the A1B and A2 SRES climate scenarios (A1B is based on lower CO_2, N_2O, CH_4, and SO_2 emissions than A2) for 2030 and 2070 (IPPC IV SRES 2007[76]). The CSIRO-Mk3.0 and MIROC-H GCMs models provide predicted values for each of the CliMond bioclimatic variables and also perform well in the generation of future climate scenarios[51]. We projected models using the 'project' function in 'rmaxent'[64] for the native + invaded models and invaded only models and visualized the resulting shifts in distributions.

Data Availability

All data was gathered from publically available sources and will be made available in the format used for analysis at the Data Repository for the University of Minnesota (DRUM; www.lib.umn.edu/datamanagement/drum).

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Author Contributions

R.D.B.R., D.M. and P.T. conceived the work. R.D.B.R. and T.L. gathered data and ran analyses. R.D.B.R. and D.M. wrote the first draft of the manuscript and all authors contributed to the editing of the manuscript.

Additional Information

Supplementary information accompanies this paper at https://doi.org/10.1038/s41598-018-38054-9.

Competing Interests: The authors declare no competing interests.

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ML2014 Project Abstract
For the Period Ending December 30, 2019

PROJECT TITLE: MITPPC Sub-project #4 Cover it Up! Using plant to control buckthorn
PROJECT MANAGER: Dr. Peter Reich
AFFILIATION: University of Minnesota
MAILING ADDRESS: 1530 Cleveland Ave.
CITY/STATE/ZIP: St. Paul, MN 55108
PHONE: 612-624-4270
E-MAIL: preich@umn.edu
WEBSITE: https://forestecology.cfans.umn.edu
FUNDING SOURCE: Environment and Natural Resources Trust Fund
LEGAL CITATION: ML 2014, Chapter 312, Article 12, Section 8

APPROPRIATION AMOUNT: $327,000
AMOUNT SPENT: $327,000
AMOUNT REMAINING: $0

Sound bite of Project Outcomes and Results
Buckthorn degrades the health of Minnesota forests. Efforts to control buckthorn generally yield only short-term benefits, since buckthorn quickly returns. We found that densely establishing native plants that have leaves early in the spring and late in the fall can shade out buckthorn and reduce the need for repeated management.

Overall Project Outcome and Result
Buckthorn is an invasive shrub that outcompetes native plants and degrades Minnesota forests. Removal of buckthorn is a common management activity but often only provides short-lived benefits since buckthorn rapidly re-establishes. In grasslands, heavily seeding native species can often restore native communities and inhibit invasion, but this approach is rarely used in forest management (Schuster et al. 2018). We investigated whether we could similarly establish enough native plants to prevent buckthorn from re-establishing in forest using three separate experiments.

First, we surveyed sites at 24 properties in Minnesota where buckthorn management had taken place to identify the most successful techniques (Wragg et al. in review). Management success was highly variable, but sites where more native vegetation had been re-established tended to have lower buckthorn abundance.

Second, we measured the growth and survival of buckthorn seedlings in a forest biodiversity experiment. There, we found that canopies that permitted less than 10% of incoming light had significantly reduced buckthorn growth and canopies that permitted less than 3% light, particularly in the spring and fall, completely excluded buckthorn (Schuster et al. 2020).

Third, we established a series of experiments across 7 sites that had recently had buckthorn removed. In those experiments, we tested how densely seeding or planting native plants affected buckthorn seedlings. After 3 years, we found that planting trees and shrubs, particularly *Sambucus* shrubs, greatly reduced light levels and excluded buckthorn (Wragg et al., Schuster et al. in prep). Other seeding and planting treatments had more moderate effects and may require additional years to become fully effective. We also found that the rarely-used herbicide fosamine ammonium was effective at controlling buckthorn (Schuster et al. in review).

The Cover It Up! project illustrates that it is possible to curate native plant communities in a way that makes them resistant to buckthorn invasion. In general, we recommend that forests be managed to promote the establishment of shrubs and trees that provide heavy shade in the spring and fall. Our findings suggest that by doing so, managers can simultaneously increase forest health, inhibit invasion, and reduce the need for investment in future buckthorn removals.

Project Results Use and Dissemination

Results were disseminated through diverse media to a wide range of stakeholders. Findings from Cover It Up! were included in five academic journal articles to date. Stories about our project were featured in media from unaffiliated parties, including KARE 11, Pioneer Press, National Park Service social media, and Science Museum of Minnesota Field Notes. Our findings were also conveyed through 12 in-person presentations for over 500 attendees.

ML 2014, Chapter 312, Article 12, Section 8, MITPPC Sub-Project #5 Project Abstract
For the Period Ending January 31, 2021

PROJECT TITLE: MITPPC #5: Terrestrial invasive species prioritization
PROJECT MANAGER: Dr. Amy Morey
AFFILIATION: Minnesota Invasive Terrestrial Plants and Pests Center
MAILING ADDRESS: 1980 Folwell Ave, Hodson Hall Rm 219
CITY/STATE/ZIP: St. Paul, MN 55108
PHONE: 406-698-7684
E-MAIL: morey041@umn.edu
WEBSITE: www.mitppc.umn.edu
FUNDING SOURCE: Environment and Natural Resources Trust Fund
LEGAL CITATION: ML 2014, Chapter 312, Article 12, Section 8

APPROPRIATION AMOUNT: $32,000
AMOUNT SPENT: $32,000
AMOUNT REMAINING: $0

Sound bite of Project Outcomes and Results

This project produced written risk evaluations of 12 terrestrial invasive species requested for review by MITPPC stakeholders and drafted a rubric for soliciting TIS review requests in the future. It also resulted in a scientific article formally describing the MITPPC prioritization process.

Overall Project Outcome and Results

In 2017, the Minnesota Invasive Terrestrial Plants and Pests Center undertook an expansive research prioritization to systematically evaluate threats posed by a wide array of terrestrial invasive invertebrates, plants, and plant pathogens and created the document, "*Minnesota's Top 124 Terrestrial Invasive Plants and Pests: Priorities for Research*," which has provided guidance on funding MITPPC research projects in subsequent years. Since its publication, many terrestrial invasive species (TIS) have been suggested for further review by stakeholders. The movement of TIS into Minnesota and their potential harms calls for a thorough review of suggested species.

Following methodology developed in the 2017 document, this MITPPC project evaluated 12 TIS submitted for review. The evaluations are incorporated into the Analytic Hierarchy Process (AHP) model used by MITPPC to rank and prioritize the TIS that threaten Minnesota's terrestrial ecosystems. AHP is a form of multi-criteria decision analysis that makes the process of selecting the highest priority threats consistent and transparent. AHP has been used by many agencies and organizations to facilitate complex decision-making. Evaluations from this project will be incorporated into the 2022 update of MITPPC research priorities. In addition, a process for soliciting stakeholder TIS review requests was outlined and provided to MITPPC leadership for future consideration. The process is intended to encourage systematic and transparent solicitation of TIS of concern from stakeholders.

Initial plans for the project also involved comparing methods of climate suitability modeling for TIS to identity a method most useful in MITPPC evaluations. In consultation with MITPPC leadership, the project instead focused on writing a formal and more detailed description of the MITPPC prioritization process outlined in the 2017 whitepaper. The manuscript was submitted and accepted to a scientific journal. The forthcoming publication will be an important resource for communicating the transparency and rigor of MITPPC research priorities.

Project Results Use and Dissemination

A technical manuscript describing the MITPPC prioritization process was submitted and accepted (pending revisions) to the Journal of Environmental Management.

An oral presentation was given at the 2020 Upper Midwest Invasive Species Conference (Nov. 2020) entitled, "Making better MaxEnt models for invasive species", which presented MITPPC-funded research on

species distribution modeling for the European Gypsy Moth. In addition, the Project Lead (Morey) was a co-author on another presentation given at the 2020 UMISC, entitled “Prioritizing Minnesota’s Top Terrestrial Invasive Plants & Pests for Research”, which presented information on MITPPC and its prioritization process.

ML 2014, Ch. 312, Art. 2, Sec. 8 Project Abstract
For the Period Ending June 30, 2022

PROJECT TITLE: Minnesota Invasive Terrestrial Plants and Pests Center
PROJECT MANAGER: Dr Robert Venette
AFFILIATION: Regents, University of Minnesota
MAILING ADDRESS: MITPPC, 1992 Folwell
CITY/STATE/ZIP: St Paul, MN 55108
PHONE: 612-301-1405
E-MAIL: venet001@umn.edu
WEBSITE: www.mitppc.umn.edu
FUNDING SOURCE: Environment and Natural Resources Trust Fund
LEGAL CITATION: ML 2014, Chapter 312, Article 12, Section 8

APPROPRIATION AMOUNT: $1,460,000
AMOUNT SPENT: $1,460,000
AMOUNT REMAINING: $0

The Project Abstract is a separate document from the work plan. Submit the Project Abstract in addition to your work plan. Remove all instructions in italics and brackets from this document before submitting.

Sound bite of Project Outcomes and Results
Funding enabled the establishment of the Minnesota Invasive Terrestrial Plants & Pests Center (MITPPC). MITPPC now drives discoveries to prevent or reduce threats posed by priority invasive species to Minnesota lands. We bring University-of-Minnesota researchers together with partners from around the state, taking a programmatic approach to make thoughtful research investments and solve complex problems.

Overall Project Outcome and Results
MITPPC, established by the Minnesota Legislature in 2014, has become a national leader in research to protect Minnesota's forests, prairies, wetlands, and agricultural lands from invasive species. Under this first appropriation, MITPPC set up its internal operations; established an advisory board, comprised of representative stakeholders from agriculture and natural resource sectors; developed a prioritization process and document upon which the RFP was based; made five research awards; and worked with LCCMR staff to appropriately document an ENRTF appropriation of this scope. Significant accomplishments include:

- Sub-project #1: Dr. Abdennour Abbas and his team developed novel detection and diagnostic tools for the oak wilt pathogen, generating patents and significant publications with spin-off applications for other invasive pathogens. These new technologies will reduce the time necessary to confirm the pathogen.
- Sub-project #2: Dr. William Hutchison and his team greatly improved our understanding of the biodynamics of the brown marmorated stinkbug, *Halyomorpha halys*. A stinkbug app ("The Midwest Stinkbug Assistant") and climate suitability models by Drs Twine and Snyder were important contributions for early detection and management of this pest.
- Sub-project #3: Drs. David Moeller and Ryan Runquist completed a deep dive into climate and range maps for 10 current and emerging invasive plants, including Palmer amaranth. Their maps can guide management decisions about surveillance and eradication efforts for these species.
- Sub-project #4: Dr. Peter Reich and colleagues have demonstrated the utility of planting native plants to help manage common buckthorn. Their findings suggest managers can simultaneously increase forest health, inhibit invasion, and reduce the need for investment in future buckthorn removals.
- Sub-project #5: Dr. Amy Morey provided critical on-going research into terrestrial invasive species (TIS) prioritization. A research publication summarizes MITPPC's unique approach to the process that has been applied to more than 200 TIS and drives its requests for research proposals.

Project Results Use and Dissemination

The MITPPC's impact can be measured by the dissemination of its applied results. In-person interviews and engagements (108 presentations around the state) and peer-reviewed publications (e.g., 12 papers in high profile journals as Restoration Ecology, the Journal of Economic Entomology, and the Journal of Biogeography) provide initial outlets to share progress of the Center. MITPPC amplifies these messages and engages broader, diverse audiences through social media and on-line content, such as MITPPC's website, Twitter account, and YouTube channel and these messages are further amplified through other outlets (e.g., local press, newsletters, etc.).

Environment and Natural Resources Trust Fund (ENRTF)
M.L. 2014 Final Work Plan

Date of Report: August 11, 2022

Final Report

Date of Work Plan Approval: July 10, 2014

Project Completion Date: June 30, 2022

PROJECT TITLE: Minnesota Invasive Terrestrial Plants and Pests Center

Project Manager: Robert Venette

Organization: Regents of the University of Minnesota

Mailing Address: Minnesota Invasive Terrestrial Plants and Pests Center, 1992 Folwell Ave.

City/State/Zip Code: St. Paul, Minnesota 55108

Telephone Number: (612) 301-1405

Email Address: venet001@umn.edu

Web Address: http://www.mitppc.umn.edu

Location: Statewide

Total ENRTF Project Budget:	**ENRTF Appropriation:**	**$1,460,000**
	Amount Spent:	**1,460,000**
	Balance:	**0**

Legal Citation: M.L. 2014, Chapter 312, Article 12, Section 8

Appropriation Language:
$490,000 in 2015 is from the environment and natural resources trust fund for the Invasive Terrestrial Plants and Pests Center requested under this act, including a director, graduate students, and necessary supplies. This is a onetime appropriation and is available until June 30, 2022. $970,000 from the environment and natural resources trust fund appropriated in Laws 2011, First Special Session chapter 2, article 3, section 2, subdivision 9, paragraph (d), Reinvest in Minnesota Wetlands Reserve Acquisition and Restoration Program Partnership, is transferred to the Board of Regents of the University of Minnesota for the Invasive Terrestrial Plants and Pests Center requested under this act, including a director, graduate students, and necessary supplies and is available until June 30, 2022.

I. PROJECT TITLE: Minnesota Invasive Terrestrial Plants and Pests Center

II. PROJECT STATEMENT:

The Minnesota Invasive Terrestrial Plants and Pests Center (MITPPC) will serve a lead role in terrestrial invasive species research – coordinating initiatives on prevention of establishment; early detection and rapid response; development of new control methods and technology; integrated pest management; and minimizing non-target impacts of control. The MITPPC mission is to offer science-based solutions to pest invasions that ensure the protection of Minnesota's healthy prairies, forests, wetlands and agricultural resources. The goal is to eliminate, reduce, mitigate and prevent the introduction, expansion, or damage caused by terrestrial invasive species in Minnesota.

The array of terrestrial invasive species (TIS) of high concern for Minnesota are numerous and diverse, and include invasive grasses, trees, shrubs, insects, earthworms, mammals, fungal pathogens, and other microbes. TIS impact every citizen in the State: emerald ash borer damages our forests and urban landscapes; weeds diminish the biodiversity of our prairies and wetlands; and pests and pathogens destroy fruit and grain harvests resulting in significant economic costs. The annual, combined economic impact of plant, animal, and microbial invasives in the U.S. is estimated at $134 billion (Agricultural and Resource Economic Review, 2006). Minnesota's share of this loss is estimated at $3 billion annually, which is typical of the 50 states.

This investment will result in a comprehensive assessment of TIS risks to Minnesota and a comprehensive, planned, multi-disciplinary approach to addressing risk. MITPPC will involve researchers from multiple disciplines, and will address invasives affecting our prairies, forests, agricultural landscapes and wetlands in urban, developing and rural contexts. The Center will identify research priorities for TIS already established in Minnesota and for those that appear likely to arrive and do harm, and develop control methods, management strategies, and policy to achieve effective outcomes. Upon the completion of an initial impact assessment, the expert panel working group will establish priorities and present requests for proposals and work-plans to conduct research to address identified priority invasive species. Proposals will be sent out for peer review to ad hoc scientific reviewers in the field of research, which will allow for rapid turnaround of proposals to expedite work to be completed. The ad hoc scientific reviewers will comment on the novelty of the research, the rigor of the proposed methods, the qualifications of the team to complete the research, and the potential impact of the research on the management of invasive, terrestrial species and will make award recommendations to the Director. The~~se~~ specific initiatives selected and their budgets will be provided to LCCMR for review.

The Center will prioritize and support multiple projects by research teams comprised of faculty, students, and staff from one of 10 participating departments. UMN faculty will work with both graduate students and post-doctoral associates on any given project. The scope of each research project will likely vary by species addressed. With this and additional planned funding, it is expected that over an eight-year period the Center will conduct an estimated 18-25 projects and train roughly 25 graduate students and postdocs.

The Center will be administratively located in the College of Food, Agricultural and Natural Resource Sciences (CFANS) in coordination with the College of Biological Sciences (CBS). Participating departments within CFANS include Entomology, Plant Pathology, Forest Resources, Agronomy & Plant Genetics, Horticultural Science, Applied Economics, Fisheries, Wildlife and Conservation Biology, and Bioproducts and Biosystems Engineering. Participating departments within CBS include Plant Biology and Ecology, Evolution and Behavior. Additionally, research will be possible on CFANS' eight research and outreach centers located in diverse agro-ecological areas of the State.

III. PROJECT STATUS UPDATES:

Project Status as of *January 31, 2015*:
As this is a new center, prior to acting on either of the activities/outcomes defined in this work plan, administrative establishment of the Minnesota Invasive Terrestrial Plants and Pests Center (MITPPC) has been essential. Thus activities to date have all related to the establishment of the Center and the hiring of a director. Administrative structure and oversight has been initiated. Financial accounts and protocols have been established. MITPPC office space on the Saint Paul Campus of the University of Minnesota in the USDA Forest Service building has been identified. A search committee was established to identify and hire a center director, and Dr. Robert Venette was hired as the inaugural MITPPC Director starting January 2, 2015. A search for an Associate Director is now underway. No ENRTF funds have been spent to-date, as the above activities are currently being paid through a General Fund appropriation, other University of Minnesota sources, and contributions from the Northern Research Station of USDA Forest Service.

Amendment Request (01/31/2015):
We are requesting a change in the project manager from Brian Buhr to Robert Venette. This change also impacts contact information (i.e., mailing address, telephone number and email address). In addition we have an amendment to the other funds listed in section VI B.
Amendment Approved: 02/06/2015

Project Status as of *June 24, 2015*:
MITPPC completed a rapid prioritization to identify lines of research that would be immediately beneficial for the management of invasive terrestrial plants and pests. The details of that prioritization are summarized under updates to Activity 1. The outcome of the prioritization provided the foundation for MITPPC's first request for proposals (RFP). The RFP was issued on April 31, 2015. Eight pre-proposals were received for a total request of $3.7 million. Additional details about the RFP, the review process, and the administration of sub-subprojects are provided under updates to Activity 2.

After a national search, Ms. Heather Koop accepted the position of Associate Director for the MITPPC. She assumed the role on May 4, 2015. This position is currently paid through a General Fund appropriation.

Amendment Request (06/24/2015):
The amendment requests include a correction to the street address of the Center; the substitution of contact phone number; and the substitution of the Center's new web address. The MITPPC budgets have been modified to reflect the anticipated future line items that will be necessary to fund selected research. Since those items are not known at this time, $1 has been inserted in those line items in order to establish budgets and sub-budgets within the University's accounting system. Once the projects have been identified and recommended for funding, the MITPPC will return to the LCCMR for review with appropriate sub-work plans and sub-work budget adjustments. The travel line item in the narrative budget has been expanded to include travel within and outside of Minnesota. Examples of possible reasons for outstate travel are provided. Actual travel will be detailed in future budget amendment requests when research projects are identified. The professional/technical/service contracts line items have been expanded to include examples of the kinds of items and services that might be purchased. One other budget adjustment corrects an earlier typographical error: the line item for "travel expenses in MN" was $13,381 and is now $34,378 which aligns with the approved budget spreadsheet.
Amendment Approved: 06/25/2015

Project Status as of *December 1, 2015*:
MITPPC has identified four inaugural research sub-projects for funding. In brief, the sub-projects are 1. "Novel Diagnostic Tools for Rapid and Early Detection of Oak Wilt" (Project Manager: Dr. Abbas Abdennour), 2. "Early Detection, Forecasting, and Management of *Halyomorpha halys*" (Project Manager: Dr. William Hutchison), 3. "Climate Change and Range Expansion of Invasive Plants" (Project Manager: Dr. David Moeller), and 4. "Cover it Up! Using Plants to Control Buckthorn" (Project Manager: Dr. Peter Reich). These sub-projects were the top-rated of eight pre-proposals that were received in response to the initial request for proposals. Sub-projects were evaluated by a panel of five faculty with no direct connection to the proposed research. Details of sub-projects were clarified in full proposals which were sent for peer review by experts outside the University of Minnesota, often outside the United States, to obtain fully impartial comments. Full proposals were modified based on the comments that were received. Additional details about the sub-projects and the review process are provided in the update to revised Activity 2.

MITPPC continues to make progress on its expanded prioritization of 120 terrestrial invasive species that threaten forests, prairies, wetlands, or agriculture.

MITPPC identified 16 members for its Center Advisory Board. Members who were knowledgeable about terrestrial invasive species, their impacts within Minnesota, and the University of Minnesota were nominated by MITPPC's Director and Associate Director and appointed by CFANS Dean Brian Buhr. Ex officio members are Commissioner Tom Landewehr, Department of Natural Resources; Commissioner Dave Frederickson, Department of Agriculture; and Dean Brian Buhr, CFANS. Named representatives for ex officio members are Ann Pierce, Department of Natural Resources; Matthew Wohlman, Department of Agriculture; and Greg Cuomo, Associate Dean for Research, CFANS. Rotating members that are internal to the University of Minnesota are Vince Fritz, University of Minnesota Research and Outreach Centers; Frances Homans, Head, Department of Applied Economics; Emily Hoover, Head, Department of Horticultural Science; Gary Muehlbauer, Head, Department of Plant Biology, College of Biological Sciences; and Bob Stine, Associate Dean, College of Continuing Education. Rotating members that are external to the University of Minnesota are Nan Bailly, Alexis Bailly Vineyards; Steve Chaplin, The Nature Conservancy; Reginald De Foe, Fond du Lac Band of Lake Superior Chippewa; Shefali Mehta, Syngenta; and Bob Owens, Owens Forest Products. The Board is chaired by Bob Stine. The Center Advisory Board will provide a plan to ensure the long-term sustainability of the Center.

Amendment Request (12/01/2015):
This amendment request removes funding for Activity 1, Catalyzing Research and Education: Conduct Net Impact Risk Assessment. The activity has been funded to-date by the General Fund appropriation, ML 2014, Ch. 312, Art. 12, Sec. 8. The MITPPC will continue to provide LCCMR with updates of the prioritization process as it progresses. It is anticipated that the process will be complete early in 2016. A white paper describing the process and results will be distributed for comment at that time. The funds allocated to Activity 1 ($25,381) will be placed in reserve for future project funding.

Secondly, this amendment request specifies four sub-projects and allocates funds totaling $1,244,801 towards them to complete research that will minimize or eliminate threats posed by terrestrial invasive species. In brief, the sub-projects are 1. "Novel Diagnostic Tools for Rapid and Early Detection of Oak Wilt" (Project Manager: Dr. Abbas Abdennour, $150,000), 2. "Early Detection, Forecasting, and Management of *Halyomorpha halys*" (Project Manager: Dr. William Hutchison, $597,795), 3. "Climate Change and Range Expansion of Invasive Plants" (Project Manager: Dr. David Moeller, $170,006), and 4. "Cover it Up! Using Plants to Control Buckthorn" (Project Manager: Dr. Peter Reich, $327,000). The sub-projects that were chosen are based on the rapid prioritization process that was described in the RFP. These sub-projects address the priority themes of detection and distribution of invasive terrestrial plants

and pests (sub-projects 1, 2 & 3); response of invasive terrestrial invasive species to climate change (sub-projects 2 & 3); and effectiveness of management alternatives for terrestrial invasive species (sub-project 2). These projects also address priority taxa identified, including the brown marmorated stinkbug, oak wilt, and a variety of noxious weeds. The sub-projects have undergone a round of internal review and a round of external review and have been modified based on comments received. In some cases, sub-project managers were asked to make adjustments to their scope of work, to strengthen the research design, or to better articulate outcomes. Additional details about the sub-projects and the review process are provided in the revised Activity 2.

Finally, the document as a whole has been updated throughout for clarity and accuracy.
Amendment Approved: 12/04/2015

Project Status as of *January 31, 2016*:
The MITPPC has focused effort on the completion of the sub-work plans and establishing child accounts for each project. The Center Advisory Board met on January 26, 2016 to review updates on the prioritization process and to continue progress with the long-term business plan.

Project Status as of *July 31, 2016*:
The MITPPC completed the initiation activities for the four research projects currently funded under this appropriation. Eh of those projects have made significant progress in the last six months. Overviews of those accomplishments are provided in status updates for Activity 2 subprojects. Detailed accomplishment reports are provided as updates to the complete subproject work plans.

Center staff and stakeholders completed a draft prioritization of terrestrial invasive species, as required under ML 2014, Ch. 312, Art. 13, Sec. 44, subd. 2. The draft, "Minnesota's Top 124 Terrestrial Invasive Plants and Pests: Priorities for Research" has been published and distributed broadly for a 30 day public comment period. Draft priorities are subject to change. Center staff will review submitted comments, make the necessary revisions, and publish the final draft. The prioritized list will be used as the basis for the next Request for Proposals, anticipated to begin in August and close in September 2016. The white paper may be found on the MITPPC website: z.umn.edu/mitppcpriorities

Additionally, the Center Advisory Board met April 29, 2016 and continued its work on a longer-term business and strategic plan for the Center.

Amendment Request: 7/31/2016:
Each of the four sub-projects made progress in the preceding months. A later start date than initially planned necessitates minor amendments to adjust three projects' timelines, budgets, and scopes of work. Those are described under "Activity 2 Subprojects" and in greater detail in the individual sub-project workplans.

The solicitation process which began last summer culminated in four projects moving forward to full proposal. Those full proposals were then externally reviewed during August and September 2015. The four projects were presented to LCCMR for review in October 2015 and a formal workplan amendment was submitted to LCCMR in November 2015 and approved in early December 2015. It should be noted that each of the projects indicated an August start date.

Once the Center's workplan amendment had been approved, the UMN finance and sponsored projects administration determined that child accounts would be established for the four sub-projects; those were operational by the end of January 2016.

Hence, the time from submission of the Center's workplan (August 2015) and establishment of sub-accounts (January 2016) made the projects original timeline approximately five months out of sync. This slight delay impacted the hiring of post-docs, as UMN policy encourages the recruiting and posting of new positions only when the appropriate accounts are established. In all cases, the hiring of post-docs (and other graduate students) was essential to getting the projects operational.

The adjusted timelines remain within their originally stated end dates and are all within the availability of the appropriation

The Upper Midwest Invasive Species Conference (UMISC) will be held in LaCrosse, WI on October 17-19. There is great interest in the MITPPC and a panel presentation will be part of the conference program. Three of the four funded projects (Sub-projects 1, 2, and 4) will make presentations on their projects. This amendment request is to allow presenters to attend the UMISC and be able to use their ENRTF travel funds to do so.
Amendment Approved: (9/9/2016)

Project Status as of *January 31, 2017*:
MITPPC's first four funded projects continued to make progress. Two projects, one by Dr. Abbas and the other by Dr. Reich made readjustments to the activities in order to accomplish their objectives. Those technical changes are described in greater detail in the sub-reports.

The Upper Midwest Invasive Species Conference was held in October and the MITPPC hosted a session on the first four projects funded. Two post-doctoral associates made presentations, as well as two faculty members.

Amendment Request (01/30/2017)
The University of Minnesota instituted a mandate that all post-doctoral associates' salaries are to be raised to a minimum of $47,476 a year in order to comply with the revised regulations governing overtime pay for salaried employees under Fair Labor Standards Act. The new regulation is effective Dec. 1, 2016. http://bit.ly/2erbdbL

As a result, there are three MITPPC-funded projects that will need to increase their salary line items (and total project allocations) to cover this unanticipated budget increase. We are requesting to budget an additional $41,921 to cover the increase .We maintain a sufficient balance in ML 2014 ENRTF to absorb the increase.

Sub-project 1: increase personnel by $14,286 from $133,306 to $147,592
Sub-project 2: increase personnel by $20,580 from $559,595 to $580,175
Sub-project 3: increase personnel by $7,055 from $159,656 to $166,711.

Additionally, we request amendments to one sub-project. Dr. Abbas and his team have redesigned two outcomes and changed the related completion dates. The goals remain the same, as does the budget and overall project completion date.
Amendment Approved: February 20, 2017

Project Status as of *July 31, 2017*:
Research teams made significant progress with research presentations, publications, as well as lab and field work. Each of the sub-projects' research has produced products that direct applied applications. Dr. Abbas' labs work in quickly identifying pathogens in the field has wide application beyond plant pathology. The Hutchison lab's work in future climatic conditions under which the serious pest brown

marmorated stinkbug, too, has the applied methodology that has wide-spread application for understanding additional pest invaders. Similarly, the modeling developing under Dr. Moeller's leadership has direct benefit to understanding the viability of invading plants. Finally, Dr. Reich and his team's work on buckthorn management has been adopted been several natural resource partners.

Project Status as of *January 31, 2018*:
MITPPC is requested two minor budget changes to three projects. MITPPC sub-project 3, Climate Change and Range Expansion of Invasive Plants requested to increase personnel costs with a decrease in travel expenses. MITPPC sub-project 4, Cover it Up! requested a slight decrease in personnel and equipment/supplies and an increase to professional services and travel. Neither amendment request impacted the timeline nor outcomes of the projects.

Amendment request (6/26/18)
The MITPPC requests that $14,000 be added to ML 2014 MITPPC sub-project 2, Early Detection, Forecasting, and Management of *Halyomorpha halys* (Brown Marmorated Stinkbug) to cover unanticipated data storage costs at Minnesota Supercomputing Institute (MSI) through the life of the research project. Processed data will continued to be stored at MSI after completion of the project and will be available for future research. This increases the professional services line item from $10,000 top $24,000 and increases the overall project budget from $618,375 to $632,375.

The MITPPC requests that sub-project 3, Climate Change and Range Expansion of Invasive Plants increase the project budget by $32, 208 for personnel (from $172,955 to $205,163) and increases the overall budget from $177,055 to $209,263. Two additional two species common tansy and wild parsnip, are MITPPC priority species and will be added to the project. Tangible outputs will be a series of maps to describe current and future variation in climatic suitability for Common Tansy and Wild Parsnip. We expect that the results of this work will improve the detection of species and the development of eradication and management plans. The project end date would be extended to June 30, 2019.

Both of these sub-project increases will be funded from the reserve line item of the ML 2014 Chapter 312, Article 12, Section 8 appropriation, decreasing the reserve from $173,284 to $127,076.

Amendment Approved (7/3/2018)

Project Status as of *July 31, 2018*:
Much progress has been made with all four sub-projects funded under this appropriation since the last reporting. Significant accomplishments include published descriptions of new techniques to (1) separate the fungus that causes oak wilt from wood chips taken from infected trees, (2) extract and purify DNA from the disease causing pathogen within 15 min directly from wood drill shavings from infected trees; (3) detect the presence of target DNA from the pathogen with nanoparticles. Also, in this period, a new app, the Midwest Stinkbug Assistant, was developed and released to assist with in-field identification of the brown marmorated stinkbug. A series of maps were generated to illustrate where the climate in Minnesota is most suitable for Palmer amaranth and other invasive plants. Multiple studies continue to show that deep shade (about 95%) kills or slows the growth of buckthorn; shade levels can be adjusted by planting native plants. Results were shared at a major outreach event with over 120 participants. Additional accomplishments and results are summarized later in this document and described in greater detail in the individual subproject work plans.

One amendment was requested for sub-project #4, which extended the timeline within the end date of the appropriation for activities 1 and 2 and made a $200 increase in supplies and materials with a commensurate decrease in travel. This amendment has been approved by LCCMR.

Amendment request (12/21/18)
We request amendments to this overall work plan to reflect previously approved amendments to subproject work plans that were made since the last progress report. Here we simply summarize the date the request was made, the nature of the amendment(s), and the official date of approval by LCCMR staff. Amendments are also reflected in the M.L. 2014 Project Budget – Overall Budget of Minnesota Invasive Terrestrial Plants and Pests Center. Modifications to that document are given the current date as some projects were amended more than once between February 1, 2018 and July 31, 2018. No amendments are requested beyond what has previously been approved by LCCMR staff. In total, modifications resulted in a reduction of the Budget Reserve from $173,284 to $17,076. Additional details about the amendments may be found in subproject reports.

Activity 2 Subproject 1 Novel Diagnostic Tools for Rapid and Early Detection of Oak Wilt (Abbas, project manager). First amendment request (4/27/2018)- The personnel line item is reduced by $2,590 and the equipment/supply line item is increased by $1,527, and the travel line item was increased by $1,063. First amendment approved (5/21/2018). Second amendment request (9/24/2018)- $110,000 is taken from the Budget Reserve and added to this research project for additional personnel time (new total after both amendments: $236,938), technical contracts (new total: $2,000), supplies (new total after both amendments: $31,081) and travel (new total after both amendments: $4,267). The timeline is extended to accommodate completion of a hand-held luminometer as described under this sub-project's Activity 3. Second amendment approved (10/4/2018).

Activity 2 Subproject 2 Early Detection, Forecasting, and Management of Brown Marmorated Stinkbug (Hutchison, project manager). First amendment request (6/26/2018)- $14,000 is taken from the Budget Reserve and added to the Professional/Technical Services/Contracts line item to cover unanticipated data storage costs associated with this subproject's activity 3. The change increases the line item to a revised total of $24,000. Funds will be paid to the Minnesota Supercomputing Institute. First amendment approved (7/3/2018). Second Amendment request (11/3/2018)- Adjustments are made within the sub-project budget to address slightly greater need for supplies (insect traps) and slightly less funding needed for computers than originally estimated. The changes simply affect allocations within the equipment/tools/supplies line item as reflected in the subproject budget. Changes do not affect the total allocation to this subproject or the Budget Reserve. Activities and outcomes for the subproject are unaffected. Second Amendment Approved (11/16/2018).

Activity 2 Subproject 3 Climate Change and Range Expansion of Invasive Plants (Moeller, project manager). Amendment request (6/7/2018)- $32,208 is taken from the Budget Reserve to provide additional personnel time to develop climate suitability maps for two additional, priority weed species, common tansy and wild parsnip (new total: $205,163). The project deadline is extended to June 30, 2019. Amendment approved (7/3/2018).

Activity 2 Subproject 4 Cover It Up! (Reich, project manager). Amendment Request (9/11/18)- Two changes are made to the subproject work plan timeline. The first is a short timeline extension for the subproject's Activity 1. This change is within the project completion deadline. The second is an extension to the timeline for completing manuscripts for the subproject's Activity 2, from 31 December 2018 to 30 June 2019, to enable the research team to fully include critical data collected in October 2018 after two full years of experimental treatments. A modest increase is made to the supply and materials budget of $200, (from $14,994 to $15,194) with a commensurate decrease in the travel line item ($10,500 to $10,300.) The changes do not affect the total allocation to this subproject or the Budget Reserve. Amendment Approved (9/19/2018).
Amendment Approved 1/23/2019

Project Status as of *January 31, 2019*:
All four sub-projects continue to make excellent progress towards achieving stated outcomes. Notable accomplishments include: 1) confirmation that a new trap design provides earlier and more sensitive detection of brown marmorated stink bug than previous trapping systems; 2) completion of the first detailed assessment of the average suitability of Minnesota's weather for Palmer amaranth, with a clear north-south gradient revealed, and projected increase in suitability statewide in the mid-term; and 3) demonstration of the benefit of deep shade to buckthorn control. Additional accomplishments and results are summarized later in this document and described in greater detail in the individual subproject work plans.

Amendment request (4/24/19)
We are requesting three amendments under this appropriation. The first amendment is for MITPPC Sub-project #2. This request increases professional services by $522 from $13,000 to $13,522 and decreases travel $522 from $15,200 to $14,678. The changes do not affect the total allocation to this subproject or the Budget Reserve. An additional request is made to change the end date of Sub-project #2 from August 31, 2019 to May 30, 2020. The new end date provides the research team with time to conduct more thorough assessments of the effects of cold temperatures on mortality of adult brown marmorated stink bugs than originally planned. A more complete model will result, and will provide a better forecast of the influence of milder winter weather, or the impact of a polar vortex, on this invasive pest. The original outcomes, timeline, and budget are not affected by this request. An additional outcome has been added to Activity 2.

The second amendment is for MITPPC Sub-project #4. This request decreases professional services by $8,750 from $ 14,750 to $6,000 and increases supplies by $346 from $15,194 to $15,540 and personnel by $8,404 from $286,756 to $295,160. The changes do not affect the total allocation to this subproject or the Budget Reserve. This request is because a budgeted second application of herbicide to conclude the project is no longer necessary and more assistance is needed than originally estimated from postdoctoral associates to complete advanced statistical analyses of the data collected through November 2018 for Activity 2. They will also refine manuscripts for Activities 1 and 3 in response to internal review feedback and complete manuscripts for Activity 2, to move project findings to publication. The team also requests a six month no-cost extension to December 30, 2019.

Lastly, pursuant to conversations with LCCMR staff, we are requesting revisions to the current and future reporting procedures to make the process as simple as possible and emphasize achievements of MITPPC-related projects while allowing LCCMR to ensure that the expenditures and outcomes described in the work plan for appropriations funded by the environment and natural resources trust fund are met. Specifically, this document will become the primary vehicle to describe research plans and report significant accomplishments of all sub-projects funded under this appropriation. Here will be found a brief overview of relevant MITPPC-related activities and a table with the current status of each sub-project. Each sub-project will be described with outcomes and activities with corresponding completion dates with enough detail to adequately convey what work is being conducted, why, and the projected impact. A budget for each sub-project will be attached to the overall work plan, however budgets for sub-projects will not report on sub-activities. Separate sub-project work plans will not be required. MITPPC will maintain copies of research addenda for each sub-project and make them available to LCCMR staff upon request. Dissemination activity will be reported with each sub-project; and overall MITTPC dissemination will be reported in the overall dissemination section of the work plan. MITPPC and LCCMR staff tested these reporting procedures for one year (2018) with appropriation M.L. 2016, Chp. 186, Sec. 2, Subd. 06a. Both parties agreed that the new procedures were more effficient (approximately 85% reduction in administrative effort) and conveyed all necessary information.

Amendment Approved 4/29/2019

Project Status as of *July 11, 2019:*
All four sub-projects continue to make excellent progress. Sub-project #1 unexpectedly discovered that the new, nanoparticle-based technology to diagnose the oak wilt pathogen can also diagnose the pathogen that causes burr oak blight. This surprising outcome is not being tested further at the moment, but demonstrates the great potential of this technology to identify a number of cryptic pathogens. Sub-project #2 has confirmed that dual-lures with panel traps are easier, cheaper, and more effective to detect brown marmorated stink bug than previous methods. Results have been incorporated into statewide and national recommendations for improved detection and monitoring of this important insect. (The Minnesota Department of Agriculture has already adopted these recommendations.) Sub-project #3 is complete. Maps describing where the climate of MN is most suitable for Palmer amaranth have undergone peer review and have been published. Maps for another nine invasive weed species have been prepared. Sub-project #4 is preparing a number of publications to describe the sensitivity of buckthorn to shading and the role of native plants in managing woody invasives.

The Center's prioritization process is designed to be flexible enough to add new species as additional threats are identified. An assessment of jumping worms (*Amynthas* spp) was completed in January 2019. Analysis through MITPPC's analytical hierarchy process revealed that these species ranked as the #4 invasive invertebrate (i.e., insects and earthworms) threat to the state. This species was eligible for research funding in the Center's 2019 call for proposals. Biological summaries for 10 new species have been prepared for prioritization.

MITPPC co-hosted the "Palmer Summit" with the Minnesota Department of Agriculture in January 2019 to describe the status of Palmer amaranth in Minnesota and the Upper Midwest and to discuss regulatory and outreach goals and options. Presentations and summaries have been shared via MITPPC's website and YouTube channels.

Amendment request (7/11/19)
We request an amendment to sub-project #2 to extend the end date for Activity 3, outcome 4 from December 30, 2018 to May 30, 2019. The postdoc who was working on this project was unexpectedly called away for three months and unable to work on the project. No salary was charged to the project during this time, but this period was too short to find other qualified staff to complete the work. The end date aligns with other project outcomes. No funding adjustments are requested.

Amendment approved 7/15/19

Project Status as of January 31, 2020:
MITPPC maintains a commitment to review and revise its prioritized list of terrestrial invasive species threats to the state. Assessments are now complete for 170 species; previously, it was 124. The revised list will be used to direct the next request for proposals from MITPPC, to be issued on January 31, 2020 with a planned proposal due date of April 30, 2020.

Of the four sub-projects supported under this appropriation, two (sub-projects 1 and 4) have completed their research and are compiling final reports. Sub-project 2 will end during the next reporting period. See below for detailed summaries of each sub-project. Notable accomplishments include: *Sub-Project #1*- a revolutionary technology was developed for the detection of invasive tree pathogens. The technology was successfully applied to the fungal pathogen that causes oak wilt. The project developed a novel method for extracting fungal DNA from wood and for using nanoparticles to detect the foreign

pathogen. The approach is cheaper and faster than traditional diagnostic procedures. *Sub-Project #2*- New, simpler, cheaper trapping systems for brown marmorated stink bug have been developed and are being used to monitor the distribution of this significant new insect. Conclusive evidence demonstrates that brown marmorated stink bug develops at cooler temperatures than previously thought but is unable to survive prolonged exposure to cold temperatures (less than ca. 10°F). The work suggests that the insect in Minnesota might be able to complete more than one generation per year, which would substantially increase the amount of damage it could cause, but only if protected overwintering sites are available. High-resolution climate maps provide highly detailed descriptions of the historical climate within Minnesota and suggest how temperature and moisture might change into the future. *Sub-Project #3*- This research generated a series of maps that show how the suitability of the climate for ten noxious weeds, including Palmer amaranth, varies across the state and through time. Southeastern and central Minnesota are typically suitable for these species. *Sub-Project #4*- This research demonstrated that light availability is a severe limiting constraint on the distribution of buckthorn. Buckthorn survives poorly in areas with dense shade (less than ~4% light). Planted vegetation can create shade that helps to suppress buckthorn growth, a vital new element for the successful management of buckthorn.

Amendment Request (1/22/2020)
We request three minor budget requests to three sub-projects, including two of which ended the end of December. These changes will bring all projects' budgets into balance.
Sub-project 1: decrease equipment/tools line item by $499 from $31,081 to $30,582 with an increase of $499 to professional services from $2,000 to $2,499.

Sub-project 2: decrease in professional services by $5,215 from $24,000 to $18,785 with an increase in equipment and tools by $2,575 from $13,522 to $16,097 and a $2,640 increase in travel from $14,678 to $17,318.

Sub-project 4: increase personnel by $656 from $295,160 to $295,816 and decrease equipment and tools by $108 from $15,540 to $15,432 and a decrease in travel by $548 from $10,300 to $9,752.

Amendment Approved 2/24/2020

Project Status as of *July 31, 2020*:
MITPPC and the University of Minnesota have experienced unprecedented times in the past six months. On January 1, 2020, MITPPC issued a new whitepaper that summarized the expanded prioritization of terrestrial-invasive-species threats to Minnesota. MITPPC issued a request for pre-proposals on January 31, 2020 that reflected these new priorities. The first case of COVID-19 was confirmed in Minnesota on March 6, 2020. The University of Minnesota cancelled all non-essential travel on March 10 and made the decision to transition to on-line instruction on March 12. These decisions put an immediate end to planned field work for a number of MITPPC projects and forced some MITPPC researchers who also teach to devote significant time to new teaching methods. The governor declared a peacetime emergency on March 13. On March 15, all University employees were directed to work from home when possible. All MITPPC staff complied. Extended reduced operations at the University began on March 23, and a Public Health Emergency was declared by the University on March 25. These decisions temporarily suspended research in campus laboratories. Sub-project managers were required to develop new operating procedures for research on campus or at field sites that ensured safety of the public and all University staff and students. Though the University currently is implementing a "sunrise" plan, reduced operations have affected progress on MITPPC sub-projects, some more than others.

With respect to the current appropriation, MITPPC has completed sub-project #2, Early Detection, Forecasting, and Management of Brown Marmorated Stinkbug. Sub-project #2 has found that the

Minnesota population of brown marmorated stink bug developed faster and survived at higher rates relative to a Pennsylvania population. The findings strongly suggest that warmer temperatures in future Minnesota springs and summers will help the insect become more widespread, abundant, and problematic on more plants. Results from the study have been used to refine in-season forecasts of brown marmorated stink bug activity, distributed by Minnesota Extension to fruit and vegetable growers through the VegEdge website.

The final abstract for subproject #1 will be submitted to LCCMR by 12/11/20.

Amendment Request (12/04/2020)

We request modifications to budgets for sub-projects #1-3 so that we can redirect those projects' unspent funds to a new project(s). Specifically, per direction from LCCMR staff on November 20, 2022, we reduce the allocation to each completed sub-project to reflect the total amount spent. No amendment to Sub-Project #4 is necessary as this sub-project spent all allocated funding. So, the amount allocated to Sub-project #1 (Abbas) changes from $274,286 to $271,911; Sub-project #2 (Hutchison) changes from $632,375 to $616,081; and Sub-project #3 (Moeller) from $209,263 to $206,335, noted here and in the budget spreadsheets. These changes return $21,597 to the reserve ($2,375 from sub-project #1; $16,294 from sub-project #2; and $2,928 from sub-project #3), momentarily bringing the reserve total from $17,076 to $38,673. The amount returned to the reserve from each sub-project, where applicable, also is noted in each sub-project's budget spreadsheet.

We will submit a revised abstract for subproject 2 & 3 by 12/11/20 to reflect these changes to their final budgets.

Please note, prior to reducing the project budget for subproject 2, we request an increase in ETS by $460 from $13,097 to $13,557 to account for a slight overspending in this category.

We then request the addition of Sub-project #5, Terrestrial invasive species prioritization (Project Manager: Dr. Amy Morey) with a budget of $32,000. The work will continue to expand literature-based research on 12 potential terrestrial invasive species threats to Minnesota. Information from this effort feeds directly into MITPPC's species prioritizations. This prioritization is a critical process that informs what research is eligible for funding from MITPPC. Funding for this sub-project comes from the reserve, reducing the reserve from $38,673 to $6,673.
Amendment Approved 12/09/2020

Project Status as of *January 31, 2021*:
Project Status as of January 31, 2021:
Sub-project 5, "Terrestrial invasive species prioritization" completed its activities during this reporting period. An additional 12 terrestrial invasive species were reviewed. The assessments and new prioritizations will be reflected in the anticipated 2022 request for proposals. The final report for Sub-project 5 accompanies this update. There are no active projects at this time. We will maintain the balance of $6,673 open in the reserve for work related to the MITPPC's mission. A future amendment request to the project will be submitted for LCCMR's review and approval before the reserve is spent. The appropriation closes June 30, 2022.

Amendment Request (2/05/2021)
We request the addition of reporting dates to align with the end date of the appropriation. Additional reporting dates are included in sections III. OVERALL PROJECT UPDATES, IV. PROJECT ACTIVITIES AND OUTCOMES (Activity 1 and the overview of Activity 2), and V. DISSEMINATION.

Amendment Approved by LCCMR 2/12/2021

Project Status as of *July 29, 2021*:
No active sub-projects are supported by this appropriation. The appropriation remains open with a balance of $6,673 for future work related to MITPPC's mission. Our intent is to use the remainder for a modest expansion to the scope of work for an ongoing MITPPC sub-project that is currently funded through other appropriations. An amendment will be proposed to LCCMR staff no later than December 31, 2021 to ensure that funds are spent properly by the close of the appropriation.

Dr. Amy Morey (MITPPC Researcher) and Director Venette published a peer-reviewed manuscript to describe the details of the process that has been used to prioritize terrestrial invasive species (TIS) for research. The process was recognized as being unique because of the approaches used to incorporate multiple stakeholder perspectives about the factors that affect the threat levels TIS pose to the state. Further, the steps taken to allow consistent comparisons among diverse species and to adjust those comparisons as new TIS threats are identified or new information about known TIS threats becomes available were judged to be novel and credible.

Dr. Morey engaged the public for comment about additional TIS to consider in the prioritization process and for feedback on previous species prioritizations. Subsequent modifications to the prioritization will be reflected in a request for proposals to be issued in January 2022.

Dr. Venette continued to describe the unique value MITPPC brings to the research process. Presentations were made to local and national audiences. Previously funded sub-project teams continue to publish finding that have previously been summarized in reports to LCCMR.

Project Status as of *November 23, 2021* (In lieu of report scheduled for *January 31, 2022*):
As indicated in the previous project status update, effort has gone into an appropriate use of the small remaining budget reserve. Expansion of any sub-projects funded under this appropriation has proven to be infeasible. Inadequate time is available to solicit requests, conduct peer reviews, and complete the work. A more productive use of the remaining funds would be for publication or open-access fees to disseminate results from MITPPC research. This idea was briefly discussed between Dr. Venette and Director Nash on September 27-28, 2021 via email. Director Nash expressed general support. An amendment to implement this idea is provided below.

MITPPC is currently preparing the language for a new request for proposals (RFP) to be issued in January 2022. The new RFP will reflect an updated list of species priorities. The updated list of the greatest invasive species threats to the state is undergoing a final round of review by the Center's Advisory Board. Review will be complete by November 30, 2021 with adjustments to the prioritization based on that feedback completed by December 31, 2021.

Timing of MITPPC's RFP is meant to coincide with LCCMR's own call for proposals. MITPPC understands that project managers who are interested in conducting research on terrestrial invasive species are strongly encouraged to apply to MITPPC rather than LCCMR. If necessary, research proposals submitted to LCCMR may be redirected to MITPPC. Thus, proposals will be due to MITPPC at least 7 days after LCCMR closes its request.

MITPPC continues to discuss progress on research for terrestrial invasive species with stakeholders. In addition to formal presentations, MITPPC staff researcher, Dr. Amy Morey was elected to serve on the Board of Directors for the North American Invasive Species Management Association. Her participation

will help to bring MITPPC's outcome-oriented research to continental-scale efforts to improve invasive species management and outreach.

Amendment request (11/8/2021)
MITPPC requests that the balance of this appropriation, $6,673 be transferred from the reserve to a Professional Services line item for MITPPC researchers to underwrite costs associated with the production or open access licensing of peer reviewed publications, enabling the research to reach a wider audience and have greater impact. Funds will be managed directly by MITPPC and will be distributed on a first-come, first-served basis with priority given to teams with no other source of support. An open call to MITPPC research teams will be issued upon approval of this amendment. Publications made possible with these funds will be reported in this section with the final project status update on June 30, 2022. A line item has been added to the budget summary to indicate the change in the intended use of the reserve.

We also request amendments throughout the document to reflect the current reporting date in lieu of the report that was scheduled for January 31, 2022.

Amendment Approved by LCCMR 12/22/2021

Project Status as of *June 30, 2022*:
MITPPC used the remaining funds in this appropriation to support the dissemination of research findings through two peer reviewed publications. The findings appear in the journals Phytopathology and Frontiers in Veterinary Science. Drs. Dean Malvick, Kathryn Bushley, and their colleagues report in Phytopathology the first evidence that three genetically distinct lines of the fungus that causes soybean sudden death syndrome occur in Minnesota. Only two of these lines are responsible for most of the spread of the disease. The findings are essential to help growers to determine how quickly the disease might spread within a field or county and to support appropriate disease response strategies. Dr. Tiffany Wolf and colleagues report in Frontiers in Veterinary Medicine the dangers of goats contracting a lethal infection by meningeal worm, the same parasite that affects moose in Minnesota. Goats are widely used for buckthorn management and may contract the parasite if they accidentally consume infected snails or slugs while grazing. (Snails and slugs are intermediate hosts for the parasite.) Infections can be lethal to goats and related ruminants. The risk of mortality from meningeal infection has increased generally since 2001. Mortality also shows strong seasonal patterns with the risk of mortality greatest in fall and winter. These findings are helpful to the growing goat industry in Minnesota and ranchers who offer goats for invasive plant management.

With the generous, supplemental support of LCCMR, MITPPC continues its research into new tools and strategies to prevent or reduce the harmful effects of terrestrial invasive species in the forests, fields, prairies, and wetlands of Minnesota. Critical additional appropriations to MITPPC through the Environment and Natural Resources Trust Fund have spurred even broader innovations that are changing invasive species management in the state. A new request for research pre-proposals was issued in January 2022 to address an updated priority list of invasive species. The extensive peer-review process to select future projects for funding is underway.

Overall Project Outcomes **and Results:**
MITPPC, established by the Minnesota Legislature in 2014, has become the national leader in university-based terrestrial invasive research. Under this first appropriation, MITPPC set up its internal operations; established an advisory board, comprised of representative stakeholders from agriculture and natural resource sectors; developed a prioritization process and document upon which the RFP was based; made five research awards; and worked with LCCMR staff to appropriately document an ENRTF appropriation of this scope. Significant contributions to this work were provided by the Minnesota General Fund and in-kind contributions from the University of Minnesota and the US Forest Service.

Each of the five research sub-projects accomplished the objectives set initially and have made important contributions to the field. Significant accomplishments include:

Sub-project #1: Dr. Abdennour Abbas and his team developed novel detection and diagnostic tools for the oak wilt pathogen (*Bretziella fagacearum*). The advances resulted in patents and significant publications that will have spin-off applications for other invasive pathogens. New tests based upon this technology will greatly reduce the time necessary to detect the pathogen, by making the technology available in the field.

Sub-project #2: Dr. William Hutchison and his team greatly improved our understanding of the biodynamics of the brown marmorated stinkbug, *Halyomorpha halys* (a regular home invader each autumn a major pest of plants). They demonstrated that the biology of the insect is different from elsewhere in the United States and provided new tools for early detection and management of this pest. A stinkbug app ("The Midwest Stinkbug Assistant") and the climate suitability models by Drs Twine and Snyder were important contributions to the field.

Sub-project #3: Drs. David Moeller and Ryan Runquist completed a deep dive into climate and range maps for 10 current and emerging invasive plants, including Palmer amaranth. Their maps can be used to help guide management decisions about surveillance and eradication efforts for these species.

Sub-project #4: Dr. Peter Reich and colleagues have shown that it is possible to cultivate native plants to manage buckthorn (*Rhamnus cathartica*) invasion. Planting shrubs, trees, grasses, or forbs will create heavy shade that will suppress (or kill) buckthorn seedlings or sprouts. Their findings suggest managers can simultaneously increase forest health, inhibit invasion, and reduce the need for investment in future buckthorn removals. These findings are being adopted by industry consultants and private landowners.

Sub-project #5: Dr. Amy Morey provided critical on-going research into terrestrial invasive species (TIS) prioritization. A research publication summarizes MITPPC's unique approach to the process. Under this research project, 12 new TIS were evaluated for prioritization and updated another 210 TIS species.

IV. PROJECT ACTIVITIES AND OUTCOMES:

ACTIVITY 1: Catalyzing Research & Education: Conduct Net Impact Risk Assessment
Description: A key foundational principle of the MITPPC will be to develop its research activities and portfolio based on net impact assessment of various invasive species and expected outcomes of intervention strategies. This approach will include consideration of pressing need, opportunity and practicality, which will allow for strategic management of the research portfolio. The Center will establish a 12-member expert panel to create risk assessment frameworks and conduct net impact

assessments that will prioritize investments in research to address existing invasive species as well as rapidly spreading invasive species that have not yet but are highly likely to enter the State. The panel will meet annually (years 1-3) to assess progress and re-prioritize as necessary.

We will create the panel using national level scientists with demonstrated research expertise (advanced degrees in related field, publications in related discipline, affiliation with recognized research centers in related disciplines). The twelve members will include eight Minnesota experts (faculty at University of Minnesota, or Minnesota government or non-governmental organizations with credentials as above) and four external experts (similar credentials as internal but from out of state). The goal is to provide input from broader national experiences with similar challenges. The external experts will receive an honorarium of $1,000 per meeting as well as travel expenses such as lodging, transportation and meals. The $1,000 includes not only the two days of on-site meetings, but also it is expected that external experts will spend significant time reviewing literature and other information regarding Minnesota's invasive species challenges. Internal experts will receive travel related and meal expenses to the extent the sessions are held off their home site and are likely to include lodging and meals.

Summary Budget Information for Activity 1:	**ENRTF Budget:**	**$ 0**
	Amount Spent:	**$ 0**
	Balance:	**$ 0**

Activity Completion Date:

Outcome	**Completion Date**	**Budget**
Establish a panel of internal and external experts to provide input on strategic direction and research priorities	Sept 15, 2015	$0
Convene expert panel to create framework and then to conduct initial assessment to establish highest priority species	Oct 15, 2015	$0
Convene expert panel annually (years 2-3) to assess net impacts of invasive species and control responses.	Oct 15, 2017	$0

Activity Status as of *January 31, 2015*:
Nothing to report.

Activity Status as of *June 24, 2015:*

By using funds from the 2014 General Fund appropriation, the MITPPC conducted a rapid prioritization in the spring of 2015 to identify immediate research needs among state agencies with primary responsibility for the management of terrestrial invasive plants and pests on public and private lands. Initial priority plants are species on the eradicate list, the control list, or the restricted noxious weed list as designated under Minnesota's noxious weed law, and initial priority pests were the brown marmorated stink bug (Halyomorpha halys) and oak wilt (caused by the fungal pathogen Ceratocystis fagacearum). Initial priority themes for research are:

- invasive species detection and distribution;
- invasive species response to climate change; and
- new approaches to management of invasive species.

These priorities were identified through a consultative process with eight representatives from the Minnesota Board of Water and Soil Resources, Minnesota Department of Agriculture, Minnesota

Department of Natural Resources, and Minnesota Department of Transportation. Each agency had generated a list of several dozen potential research themes and topics. From these lists each agency self-selected their top four research priorities. MITPPC advised that a research topic should be considered a priority if it (i) would help the agency achieve its mission more effectively, (ii) would be of benefit to another agency (iii) could be supported by the agency financially or through in-kind contributions, and (iv) could be completed with the capacity at the University of Minnesota. Agency priorities were vetted during a joint meeting on March 26, 2015. The initial prioritization was complete by April 15, 2015. The prioritization provided the basis for MITPPC's first request for proposals. More details about those proposals are provided under updates to Activity 2.

A more expansive research prioritization was initiated in May 2015 to systematically evaluate threats posed by a wider array of terrestrial invasive plants, pathogens, and insects/arthropods than could be completed during the rapid prioritization. The more expansive prioritization will be used to allocate the remaining research funds from the M.L. 2014 ENRTF appropriation and the M.L. 2015 ENRTF appropriation. Twelve panelists were identified, six from the faculty at the University of Minnesota and six program managers with advanced degrees from partner agencies (Minnesota Departments of Natural Resources and Agriculture). In total, these panelists will identify 120 significant invasive plants, pathogens, or insects/arthropods that threaten Minnesota's agriculture, forests, wetlands, or prairies. An Analytical Hierarchy Process (AHP) will be used to rank these threats. AHP is a form of multi-criteria decision analysis that makes the process of selecting the highest priority threats consistent and transparent. AHP has been used by many agencies and organizations to facilitate complex decision making. In brief, the twelve member panel will engage in a facilitated discussion about criteria by which terrestrial invasive plants and pests should be considered a high threat (e.g., spread rate, reproductive rate, and impact potential) and the relative importance of each criterion. Each of the criteria will be applied to the 120 plants, pathogens, and insects/arthropods through reviews of the literature and consultations with relevant experts. National experts will be consulted to identify the greatest research needs for these priority taxa.

Activity Status as of *December 1, 2015*:
Activity 1 will no longer be funded under this appropriation. This activity has been funded to-date by the General Fund appropriation, ML 2014, Ch. 312, Art. 12, Sec. 8, and it will continue to be so until completion. The MITPPC will continue to provide LCCMR with updates on this Activity and its outcomes as it progresses. It is anticipated that the process will be complete early in 2016.

Our 12-person, pest prioritization panel met on September 8, 2015 to use the analytical hierarchy process to identify terrestrial invasive species that are most likely to invade Minnesota, cause the greatest harm if they invaded the state, and be managed more effectively through additional research. Upon further discussion, the panel encouraged comparisons among species based on their unmanaged biological threat. The panel identified nineteen criteria to measure "unmanaged biological threat." As part of the analytical hierarchy process, the relative importance of each criterion was determined by a questionnaire submitted to all panelists. The questionnaire presented pairwise comparisons of the criteria. Each panelist was asked to determine whether the paired criteria were equally important (given a value of 1), and if not, which criterion was more important on a scale of 2 (slightly more important) to 9 (extremely more important). Responses from the panel were analyzed with Comparion Core software, and results presented to the panelists. The results reflect differences in the relative importance of each criterion to determine unmanaged biological threat (for example, the panel generally felt that potential impacts were more important than the likelihood that a species would invade the state when assessing threat). A team of six graduate students was then hired to assemble published information about the 120 species and provide summaries of that information with respect to the 19 criteria. Those summaries will then be used in the analytical hierarchy process to compare and rank all 120 species. A

white paper that describes the process and outcomes will be prepared and distributed for public comment. The final species rankings will be used to set research priorities for the Center.

Activity Status as of *January 31, 2016:*
Graduate students provided summaries of relevant literature for each of the 120 species.

Activity Status as of *July 31, 2016:*
The prioritization process has been completed and is out for a 30 day public comment period, closing July 29, 2016. The MITPPC will issue the final version of the white paper subsequent to review and revision provided by those critiquing the paper. This document will be used as the basis for setting research funding in the 2016 Request for Proposals. The prioritization of Minnesota's top 124 terrestrial invasive species may be found here:
z.umn.edu/mitppcpriorities

Activity Status as of *January 31, 2017*:
The prioritization process is complete with the publication of the document, "Minnesota's Top 124 Terrestrial Invasive Plants and Pests: Priorities for Research." This document was the basis for the August 2017 Request for Proposals. The prioritization of taxa will be reviewed and updated on an annual process. The document may be accessed here: www.mitppc.umn.edu

Activity Status as of *July 31, 2017:*
No activity under this activity.

Activity Status as of *January 31, 2018:*
The MITPPC began revisiting the prioritization process during the last six months. Two graduate students were hired to conduct literature reviews on 60 species added to the list. The additions to the list resulted from an open request to scientists, land managers, and others interested in terrestrial invasive research. We anticipate completing this work by the next reporting period. Any revisions to the current list of species' ranking will be used for next year's RFP.

Activity Status as of *July 31, 2018*:
Graduate students continue to review literature of additional invasive plants to consider in the prioritization. The students note significant complications with finding relevant literature. Summarizing available literature is progressing more slowly than anticipated.

Activity Status as of *January 31, 2019*:
Graduate students completed draft assessments for 21 additional invasive species that have been proposed for prioritization by MITPPC. MITPPC has contacted a postdoctoral research associate with extensive experience in invasive species research to review and revise these documents. In addition, she will complete new assessments for an additional set of invasive species proposed for prioritization. In this past activity period, MITPPC also received a formal review of the literature on jumping worms, *Amynthas* spp., a growing threat to the state. The review was provided by the MN Department of Natural Resources and the University of Minnesota. The review addressed each of the criteria considered by MITPPC in its prioritization process. This information was incorporated into the Analytical Hierarchy Process (AHP), an objective means to set priorities. (The capacity to readily incorporate new information into AHP is a benefit of this approach.) *Amynthas* spp. received a score of 86.97 (out of 100), which placed it at #4 on the list of the most threatening insects and other invertebrate animals to the state. The high ranking of this species will make it an appropriate focus of study among research proposals solicited this coming April.

Activity Status as of *July 11, 2019:*
Work was begun to update the prioritization process in June 2019. Dr. Amy Morey, post-doctoral associate, will undertake the research. Dr. Morey will conduct literature reviews for an additional 46 species of pathogens, plants, and pests that have been suggested by a broad array of citizens and stakeholders over the last 18 months. Some of those species to be examined are currently present and/or established in the state and others are relatively new. Ten draft assessments have been prepared. This update to the prioritization will be complete before the issuing of MITPPC's next Request for Proposals. The updating of the prioritization process is being funded by M.L. 2015, Chp. 76, Sec. 2, Subd. 6a.

Activity Status as of *January 31, 2020:*
The MITPPC co-sponsored a symposium with the Institute on the Environment on September 25, 2019 that examined the utilization of Unmanned Aerial Vehicle (UAV) in the detection and distribution and management of terrestrial invasive species. Sixty people participated from industry, government, and academia. The symposium is archived and available to view on the MITPPC You-tube channel.

Dr. Morey's research to expand the number of species that are prioritized and ranked is now concluded and is described under ML 2015, Chp. 76, Sec. 2, Subd. 6a status update. This information will inform the forthcoming January 2020 MITPPC Request for Proposals.

Activity Status as of *July 31, 2020*:
MITPPC used the revised, expanded prioritization as the basis for a new Request for Proposals. The RFP closed on April 30, 2020. Funding to support those efforts will come from M.L. 2018, Chp. 214, Art. 4, Sec. 02, Subd. 06a . Outcomes of the RFP are provided in the status report for that appropriation.

Project Status as of *January 31, 2021*:
Several new species have been reviewed. Each of the new assessments has been prepared as a standalone document. These documents will be made available for public comment. The final assessments (reflecting revisions from those comments, if necessary) will be used to update the overall prioritization. The revised priorities will be reflected in the request for proposals to be issued in January 2022. A technical paper describing the details of the prioritization has been tentatively accepted in a peer-reviewed publication, pending satisfactory revision.

Project Status as of *July 29, 2021*:
Dr. Morey also worked with MITPPC communications staff to solicit nominations from the public about additional species to consider in the prioritization process or to comment on previous species assessments. In April 2021, a news release was distributed to request public input (https://mitppc.umn.edu/news/mitppc-requests-public-input-high-priority-species) with follow up requests submitted through MITPPC's newsletter and listserv. A total of 24 unique submitters (determined by name or affiliation) provided feedback. We were modestly pleased with the response rate, given the highly technical nature of the request. While 16 new species were proposed for assessment, only eight met the minimum criteria to be considered for evaluation. Eleven comments were received on existing assessments, but none of the comments affected species rankings. The updated prioritization will be used in a request for proposals to be issued in January 2022.

Project Status as of *November 23, 2021* (In lieu of report scheduled for *January 31, 2022*):
An initial, updated list of prioritized species was prepared and presented to MITPPC's Center Advisory Board on October 25, 2021. Changes to the list were the consequence of new species being nominated for evaluation, new information becoming available about previously evaluated species, and a slight change in the calculation of the priority score for each species. This final, technical change was a positive

outcome of peer review as MITPPC published its process (see: Morey & Venette. 2021. Journal of Environmental Management 290: 112556). Comments from the Advisory Board, if any, are expected by November 30, 2021. Any necessary revisions in response to those comments will be complete by December 31, 2021.

Project Status as of *June 30, 2022*:
A new request for pre-proposals (RFP) was issued January 1, 2022 to address the updated list of priority species. (See https://mitppc.umn.edu/invasive-species-prioritization [last accessed August 10, 2022] for the species list). Twenty-one pre-proposals were submitted by April 29, 2022 and reviewed by independent researchers from the University of Minnesota. Researchers requested $9,609,980, nearly twice the funding available to MITPPC at this time. Based on the feedback of the reviewers, twelve teams were invited to submit full research proposals by August 7, 2022. Full proposals are in the process of being reviewed by national and international research experts outside the University of Minnesota. A slate of new research sub-projects will be presented to LCCMR staff for review and approval in Fall 2022.

Final Report Summary:
The Minnesota Invasive Terrestrial Plants and Pests Center has been a resounding success. The Center has demonstrated how research on terrestrial invasive species might be reimagined and redirected. The objective prioritization process developed by MITPPC ensures that research is directed to the greatest invasive species threats to the state. This process sets MITPPC apart. New species are regularly considered for research, and new information about previously evaluated species is routinely incorporated. To date, MITPPC has evaluated 227 invasive plants, pathogens, or invertebrates (primarily insects) that are in Minnesota or are poised to arrive. Only the top 20%, the worst of the worst invaders, are eligible for funding. Research teams must address common needs to detect and characterize the distribution of invasive species in the state, to develop new management alternatives, to characterize the consequences of future conditions for invasive species in the state, and to understand socioeconomic factors that affect invasive species management. These clear priorities have attracted diverse researchers from across the University of Minnesota with unique talents to propose truly innovative solutions to invasive species challenges.

ACTIVITY 2: Launch research on high priority, established terrestrial invasive species and rapid response for the prevention of establishment of new threats.

Description: Upon the completion of an initial impact assessment, the expert panel working group will establish priorities and present requests for proposals and work-plans to conduct research to address identified priority invasive species. Proposals will be sent out for peer review to ad hoc scientific reviewers in the field of research, which will allow for rapid turnaround of proposals to expedite work to be completed.

The Center will initiate and/or accelerate coordinated, applied research according to the prioritized list of pest and plant species that threaten Minnesota's prairies, urban and rural forests, wetlands, and agricultural resources. Depending on the net impacts associated with each species, research may include new control methods including bio-control and technology, development of integrated pest management tools that minimize non-target impacts of control, early detection of and/or rapid response to new threats, and establishment prevention. The Center infrastructure is vital to improving Minnesota's capacity and response time to preventing and limiting introduction of new terrestrial invasive species. All research projects will include an analysis of any consequences related to the management of prioritized species to the State's non-target flora, fauna or our soils, water and climate.

Workforce development and training experts in invasive species management is also critical. A core component of each project will be funding of graduate students and postdoctoral associates to work with existing faculty. Since University faculty are expected to acquire grants that cover their research salary, existing faculty are accounted for in the budget at 25% time in their role as the project leader. Providing salary through these awards will secure faculty time and intellectual effort in the projects, assuring that we are attracting the resources to provide project design, effort, and mentoring of the graduate students and post-docs in their research development. We do not anticipate hiring any new faculty for the projects.

The Center will support multiple projects by research teams, each comprised of a UMN faculty member from one of the participating departments, one graduate student and one postdoctoral associate. Estimated funding per project will be $180,000-210,000 per year, for three to four years. We expect this to result in two to three projects depending upon the priority identified by the risk assessment planning. It is expected that per project expenses for established invasive species will be higher as compared to prevention strategies. As the priorities are established and research projects are reviewed and approved for funding as we describe here, the project specific work plan activities and budgets will be updated.

Summary Budget Information for Activity 2:	**ENRTF Budget:**	**$1,460,000**

Activity Completion Date:

Outcome	**Completion Date**	**Budget**
RFP released for first phase of projects	April 2015	$0
First four research projects selected	September 2015	$0
Research findings for first four projects	May 15, 2020	$1,460,000

Activity Status as of *January 31, 2015*: No activities to report.

Activity Status as of *June 24, 2015:*
After review and approval by LCCMR staff, MITPPC's first request for proposals was issued on April 30, 2015. The complete request for proposals, including descriptions of priorities and the process by which projects will be selected, is attached as Appendix A to this work plan, on file with LCCMR. The rapid prioritization and associated request for proposals will be used to allocate up to $1.2 million awarded to MITPPC through the M.L. 2014 ENRTF appropriation.

Eight pre-proposals were received on May 22, 2015. Those pre-proposals are currently being reviewed by a five member panel of University faculty who do not have a conflict of interest with the proposals submitted. Their evaluations will be used to determine which research teams will be invited to submit full proposals with the proposed or a modified scope of work. Full proposals will be reviewed by three experts outside of the University for scientific novelty and rigor. Final funding recommendations will be presented to the Center Advisory Board for review and consent. The intent is for initial projects selected for funding under the M.L. 2014 ENRTF appropriation to be reviewed by LCCMR and begin by August 15, 2015.

Research projects funded by MITPPC will be treated administratively as sub-projects under this work plan. As research sub-projects are identified for funding, new sub-project work plans and budgets will

be submitted to LCCMR by the new investigators for review and approval. Regular activity updates and budget updates will be provided by sub-project leaders directly to LCCMR and to MITPPC. This overarching work plan and budget will be updated accordingly to include general progress of the Center and a synopsis of activities completed by each sub-project. The budget updates for this overall work plan will provide summaries of expenditures (by budget line item) for each sub-project. Details on expenditures will be found in sub-project reports.

Activity Status as of *December 1, 2015:*
Four projects were recommended for funding. These selected proposals are to be considered sub-projects with respect to this work plan. A detailed overview of the sub-projects is provided below and each sub-project has its own work plan. Sufficient funding remains in reserve to support at least one additional project. The remainder of this activity update describes how these projects were reviewed and revised prior to final selection.

MITPPC received comments on the eight pre-proposals from a panel of five University of Minnesota faculty members with research expertise on invasive species and no connection to the proposals. Reviewers rated proposals on ten criteria:

1. FUNDING PRIORITIES: Responds to research priorities for the MITPPC outlined in the RFP;

2. MULTIPLE BENEFITS: Delivers multiple benefits to Minnesota's environment and natural resources;

3. OUTCOMES: Identifies clear objectives likely to result in measurable, demonstrated, and meaningful outcomes that have clear relevance to invasive terrestrial species management in Minnesota;

4. KNOWLEDGE BASE: Contributes to the knowledge base or disseminates information that will benefit other efforts;

5. EXTENT OF IMPACTS: Results in broad, long-term impacts of statewide or regional significance;

6. INNOVATION: Employs or demonstrates innovative approaches to more effectively and efficiently solve specific environment and natural resources issues;

7. SCIENTIFIC/TECHNICAL BASIS: Reflects current scientific and technical knowledge, standards, and best practices;

8. URGENCY: Addresses an issue for which immediate future action is necessary and essential to avoid undesirable consequences;

9. CAPACITY AND READINESS: Demonstrates capacity and readiness for efforts to be managed and completed in a timely, accountable, and effective manner; and

10. LEVERAGE: Leverages collaborative partnerships and additional efforts, resources, and non-state funds. For each criterion, reviewers rated the proposal from 5 (best possible) to 1. Proposals were then ranked by score totals. Top-rated projects were selected relative to constraints from the self-imposed funding cap which limited the first round of funding to $1.2 million to allow a reserve for research on a potential emerging issue.

Four teams were invited to submit full proposals. Revisions to proposals and budgets were requested based on initial reviewers' comments received. Full proposals were received on July 17, 2015. We then sent the proposals for review by subject matter experts outside Minnesota, often outside the United States, to obtain fully impartial comments. External reviewers were asked to comment on the novelty of the research, the rigor of the proposed methods, the qualifications of the team to complete the research, and the potential impact of the research on the management of terrestrial invasive species.

Final comments on all proposals were received in September 2015. Project teams were asked to modify proposals and address external reviewers' comments.

Revised proposals were received in October 2015 and were recommended for funding. A detailed overview of the sub-projects is provided below. These selected proposals are to be considered sub-projects with respect to this work plan. Detailed sub-project work plans and budgets will be submitted to LCCMR for review and approval. The details about each sub-project work plan will be included as attachments to this document. Regular activity updates and budget updates will be provided by sub-project leaders and MITPPC to LCCMR. This overarching work plan and budget will be updated accordingly to include general progress of the Center and a synopsis of activities completed by each sub-project. The budget updates for this overall work plan will provide summaries of expenditures (by budget line item) for each sub-project. Detailed sub-project reports and associated budget updates will be prepared by investigators in cooperation with the MITPPC Director and Associate Director. MITPPC will provide LCCMR with updates to this overall work plan and each sub-project as a single packet.

Questions have been posed by LCCMR staff regarding the relationship between two recommended projects and former LCCMR appropriations for similar lines of research. The first question is about "Early Detection, Forecasting, and Management of *Halyomorpha halys*." This project differs from previously funded BMSB projects by greatly expanding the monitoring effort by engaging staff from the Minnesota Integrated Pest Management (IPM) program and the Minnesota Independent Crop Consultants. The project will use several monitoring devices, such as pheromone traps and the Minnesota black-light trap network. The project will also utilize direct observations by crop consultants and on-farm observations by growers. Additionally, all observations will be facilitated by the new BMSB App. This new app will include the top 10 stinkbugs in Minnesota and will facilitate rapid data entry and checking to the google-based EDD maps.

The second question is about "Cover it Up! Using Plants to Control Buckthorn." The primary goal of the 2010 ENRTF appropriation, "Healthy Forests to Resist Invasion" was to identify forest characteristics that would be effective deterrents to invasive plants. The research demonstrated that "preventive environmental care" was a line of research worth further exploration. The studies showed that buckthorn was most prevalent in sites with little leaf litter, where there was an abundance of seed, and in which native plant diversity was low. The currently proposed research picks up this finding to determine whether post-removal plantings of native seed and plants to create an abundance of dense cover will help with longer-term and cost-effective buckthorn control.

Note that the balance of funds from Activity 1 will be held in the reserve line item for future allocation to one or more additional sub-projects.

Activity Status as of *January 31, 2016:*
Sub-workplans have been approved by LCCMR. Work is currently underway with finance and Sponsored Project Administration to establish child accounts. LCCMR approval dates for each sub-project are provided in the sub-project updates.

Activity Status as of *July 31, 2016:*
Work on the four sub-projects began in early 2016. Initial activities focused on the hiring of post docs and students. All sub-projects have initiated research. Overviews of those accomplishments are provided below in status updates to Activity 2 subprojects. Detailed descriptions are provided in status updates to the sub-project work plans.

In May 2016, LCCMR staff contacted MITPPC for its thoughts on several proposed terrestrial invasive species proposals before the commission. MITPPC submitted those comments addressing only the research components of those proposals. The terrestrial invasive species prioritization was not yet completed at the time of ENRTF FY 18 proposal deadline nor at the time of Dr. Venette's comments on those proposals. A potential conflict of interest was declared by Center director Rob Venette, who is a co-PI on three of the proposals that were before the commission. The MITPPC did not have a proposal under consideration in the ML 2017 ENRTF recommendations, but given the ENRTF funding history of the MITPPC, we are cognizant of the potential for conflict of interest to arise when a Center staff is a co-PI on a project under funding consideration by the Commission.

Activity Status as of *January 31, 2017*:
The four funded projects continue to make significant progress on their projects. Overviews of those accomplishments are provided below in status updates to Activity 2 subprojects. Detailed descriptions are provided in status updates to the sub-project work plans.

Activity Status as of *July 31, 2017:*
The four research projects made significant gains over the preceding six months. Overviews of those accomplishments are provided below in status updates to Activity 2 subprojects. Detailed descriptions are provided in status updates to the sub-project work plans.

Activity Status as of *January 31, 2018:*
The four research projects made significant gains over the preceding six months. Overviews of those accomplishments are provided below in status updates to Activity 2 subprojects. Detailed descriptions are provided in status updates to the sub-project work plans.

Activity Status as of *July 31, 2018*:
All four sub-projects continue to make significant progress as described below in the summaries of sub-project activities.

Activity Status as of *January 31, 2019*:
Details on each sub-project can be found in the summaries below.

Activity Status as of *July 11, 2019:*
Significant progress has been made by each of the four sub-projects under this appropriation. Sub-project 3 has completed its work and is preparing for the final report. Sub-projects 2 and 4 have completed many of their outcomes and are in the process of analyzing and synthesizing their work for publication and dissemination. Details on each project may be found in the summaries that follow.

Activity Status as of *January 31, 2020:*
Sub-projects 1 and 4 have now completed their research and will begin filing their final reports. Sub-project 2 will end during the next reporting period, thus completing the research funded under this appropriation. Details on each sub-project may be found in the summaries that follow.

Activity Status as of *July 31, 2020*:
Sub-project 2 has now completed its research. Details may be found in the summary below.

Activity Status as of *January 31, 2021*:
See summaries of accomplishments below.

Final Report Summary:
All sub-projects funded under this appropriation achieved the intended outcomes. New technologies were developed for the detection and diagnosis of the pathogen that causes oak wilt. A new app was developed to identify and report brown marmorated stink bug, and new tools were developed to forecast stinkbug activity now and into the future. New maps were prepared to show where 10 invasive plant species, including Palmer amaranth, might spread in Minnesota if left unmanaged, subject to current and future climate constraints. Planting native plants to compete for light is an integral component of buckthorn management; research demonstrated the efficacy of the approach with native trees, shrubs, grasses, and forbs. MITPPC developed a unique, rigorous approach to prioritize terrestrial invasive species. The prioritization process reflects diverse perspectives of several stakeholders and has been applied to more than 200 species. New species can be added to the process and new information about previously evaluated species can be incorporated without undoing work on other species.

ACTIVITY 2 SUB-PROJECTS

SUB-PROJECT 1: Novel Diagnostic Tools for Rapid and Early Detection of Oak Wilt
Project Manager: Dr. Abdennour Abbas
Description: This project will develop new assay technologies for rapid and early detection of the invasive fungus *Ceratocystis fagacearum*, causal organism of oak wilt.
Sub-project work plan approval date: January 12, 2016
Sub-project budget: $271,911

Outcome – Activity 1: Selection and Identification of DNA aptamers for *Ceratocystis fagacearum* (oak wilt)	**Completion date**
Development of a chemiluminescence assay for DNA detection	3/30/2016
Proof-of-concept of the new detection technology with *Ceratocystis fagacearum*	12/30/2016
Activity 2: Application of the new assay for the detection of oak wilt	
Demonstration of the detection of oak wilt on real samples using the new assay	5/30/2017
Characterization of the analytical parameters of the new assay	7/15/2017
Activity 3: Development of a rapid cell and DNA extraction methods from wood chips and shavings	
Demonstration of rapid separation of fungal cells from wood chips	12/31/2019
Demonstration of rapid extraction of DNA from fungal cells	12/31/2019

Sub-Project Status as of *January 31, 2016:*
The sub-work plan was approved by LCCMR on January 12, 2016. Efforts are now underway to establish a child account and to begin the research.

Sub-Project Status as of *July 31, 2016:*
A postdoctoral research associate (Dr. Renu Singh) was hired to work on the identification of new aptamers for *Ceratocystis fagacearum.* The identification of the aptamers is still in progress and will likely need two more months from the completion date indicated in the work plan (July 30, 2016.) However, the project does not need extension as other objectives have already been reached. This includes the development of new rapid method for the immobilization of the fungus on solid surfaces. This step is important for the detection of new DNA aptamers for the fungus of interest.

Principal investigators, Renu Singh and Abennour Abbas prepared a manuscript for publication related to the project, “Facile and rapid immobilization of microorganisms.” The team will present on research at the Upper Midwest Invasive Species Conference in October 2016.

Additional funds were leveraged for this project from a UMN grant-in-aid program ($45,552) and from the Minnesota Turf and Grounds Foundation ($10,000)

Sub-Project Status as of *January 31, 2017*:
This project is fine-tuning its focus on the detection of fungal DNA rather than fungal cells that require aptamers or antibodies. This change does not impact the outcomes nor the timeline for the project.

Sub-Project Status as of *July 31, 2017:*
Two of the four outcomes have been completed in this project: the development of microbial separation method from wood chips and the development of the rapid detection system. Both elements are the topics of two peer-reviewed academic publications (in progress.)

Activity Status as of *January 31, 2018:*
The project aims at developing a field-testing platform for rapid detection of oak wilt caused by the fungus *C.fagacearum*. Over the last year, we have developed a technology for fungi and fungal DNA extraction from wood chips and another technology for rapid DNA detection using chemiluminescence. We are currently working on combining these two technologies to develop a portable DNA extraction and detection platform, to enable field detection of oak wilt within one hour using a hand-held luminometer.

Activity Status as of *July 31, 2018*:
The MITPPC project "*Novel Diagnostic Tools for Rapid and Early Detection of Oak Wilt*" started in June 2016, with the purpose of developing a new technology for rapid and field detection of *Ceratocystis fagacearum*, the causal agent of Oak wilt. Early diagnosis of infected trees will help stop the spread of the disease and minimize the inherent cost for municipalities, counties, private property owners and the State. While conventional methods for oak wilt detection are costly, time-consuming or labor-intensive, the most commonly used immunoassays are not commercially available for oak wilt fungus, because of a lack of specific antibodies.

Within two years of research, we have developed and successfully tested 3 technologies: (1) a rapid method to separate *Ceratocystis fagacearum* fungal cells from wood chips obtained from infected trees, (2) a technology that enables the extraction and purification of *Ceratocystis fagacearum* DNA within 15 min directly from wood drill shavings of infected trees, and (3) a bioassay technology that enables DNA identification in less than 30 min using a hand-held reader. The three technologies offer a cheaper and faster alternative than commercially available tools, while offering equivalent or better performance. With some additional work, two of the developed technologies can be combined to offer a portable DNA extraction and identification platform for field detection of oak wilt.

Activity Status as of *January 30, 2019*:
The major accomplishments of this project relative to project objectives include:
Demonstrate the reproducibility of a new method of to extract fungal DNA from wood chips from wilted red oak and other species (bur and white oak): We have demonstrated that new DNA extraction method is reproducible and works well with red, bur and white oak. Our hypothesis is that the problems previously encountered with DNA-detection of the oak wilt pathogen in white and bur lie mostly with the spotty distribution, therefore sampling errors, not with the substances in the wood or any potential inhibitors. We believe that if we can find good positive samples of white and bur oak this coming summer with confirmed cultures, the techniques should work for them, too. Maybe bur and white should have more sampling locations and clearly streaking wood before use.
Demonstrate the sensitivity and specificity of a new DNA detection method using chemiluminescence: Over the last two months, we synthesized new nanoparticles functionalized with newly designed DNA probes to improve the specificity of the assay to detect DNA from the oak wilt pathogen. We have also demonstrated that the new assay can differentiate between target and non-target DNA. However, the specificity of the assay still needs improvement. We have moved from detecting synthesized DNA targets to working directly on the detection of DNA extracted from pure cultures of the oak wilt pathogen. The first results obtained are encouraging and we expect the completion of this activity by the end of February. A demonstration of the new assay to detect DNA from the oak wilt pathogen extracted from wood chips is planned for March 2019.

Overall, there is a delay of one month due to a change in project personnel but the results obtained over the last two months are highly encouraging, and we expect to reach the project objectives without time or budget extension.

Activity Status as of *July 31, 2019*:
In phase I and II of this project, we developed a novel nanoparticles enhanced chemiluminescence (NEC) assay for the fungal pathogen that causes oak wilt, *Ceratocystis fagacearum* (*C. fag*).. The major accomplishments in Phase II include the confirmation of previous results and optimization of various assay parameters, including luminol concentration, nanoparticles size (3-5 nanometers) and redesign of DNA probes. We will be conducting field testing of *Ceratocystis fagacearum* (*C. fag*) this summer. We unexpectedly discovered that under slightly different test conditions (pH) the technology can also detect the presence of *Tubakia iowensis*, the causal agent of bur oak blight.at a limit of detection of 200 femtomolar (very low concentration.) The results suggest that we can detect both *C. fag* and *T. iowensis* using a single probe by simple buffer assignment.

Activity status as of *January 31, 2020:*
Tree diseases caused by invasive pathogens cost hundreds of millions of dollars annually to the US. Thus, early and rapid disease detection of invasive forest pathogens is expected to have a significant economic impact by preventing the spread of diseases and the conservation of natural resources. In phase I and II of this project, we developed a novel Nanoparticles Enhanced Chemiluminescence (NEC) assay. The major accomplishments of phase II in last 6 months include: **(1)** Combination of the DNA extraction using NaOH protocol with NEC assay detection. **(2)** Application of the NEC assay on real-world samples (wood chips from healthy and infected trees) and determination of the sensitivity (88.8 %) and specificity (73%) of the NEC assay on real world samples. **(3)** Optimization of the reaction conditions. Additionally, MITPPC phase III proposal has been approved to expand the NEC assay to various invasive forest pathogens of high priority to Minnesota and conduct third party validation of the technology.

Final report summary:
Oak trees (*Quercus* spp.) play a significant role in the ecosystem and are considered economically important for several reasons. They are prone to oak wilt disease, caused by the fungus, *Bretziella fagacearum*, which is of huge concern due to the reduced profitability in their production. Affected trees cannot be cured and so, early, and rapid identification of the infection is necessary to prevent spreading. The objectives of this study include the development of cell separation method of woodchips and DNA extraction method, followed by the development of a rapid detection assay in combination with a handheld system. Infected and healthy red oak wood chip samples were collected from different parts of Minnesota followed by DNA extraction and testing using the chemiluminescence-based chemical assay. In phases I and II of this project, we developed a novel Nanoparticles Enhanced Chemiluminescence (NEC) assay. The major accomplishments include: **(1)** Combination of the DNA extraction protocol with NEC assay detection. **(2)** Application of the NEC assay on real-world samples (wood chips from healthy and infected red oak trees) and determination of the sensitivity (88.8 %) and specificity (73%) of the NEC assay. **(3)** Optimization of the reaction conditions. This research has resulted in two patent applications, with a third being contemplated. Additionally, MITPPC phase III proposal has been approved to expand the NEC assay to various invasive forest pathogens of high priority to Minnesota and conduct third party validation of the technology. The major impact of this project will be the improvement of diagnostic capabilities of plant diagnostic clinics and laboratories by offering a highly sensitive and cost-effective tool for rapid identification of oak wilt. The spread of the disease can be stopped at an early stage by administering treatments and implementing preventative measures. The proposed technology will help protect Minnesota natural resources and reduce the financial burden of oak tree removal.

SUB-PROJECT 2: Early Detection, Forecasting, and Management of *Halyomorpha halys* (Brown Marmorated Stinkbug)
Project Manager: Dr. William Hutchison

Description: A multi-stakeholder, comprehensive approach for early detection and forecasting, via phenology and climate change models, to improve the timing of management strategies for the Brown Marmorated Stinkbug
Sub-project budget: $616,081

Sub-project work plan approval date: January 12, 2016

Outcome – Activity 1: Early Detection, distribution (EDD) and mapping of BMSB distributions	**Completion date**
Develop, field test EDD system for MN, including modified BMSB App and website	12/31/16
Trap procurement; establish "dual-lure" pheromone & light trap network in MN	12/31/19
Collate the EDD data and maps for independent validation of models for MN (see Activity 2 for this sub-project)	12/31/2019
Outcome – Activity 2: Develop and validate biological parameters for BMSB response to temperature for improved pest management via predictive models	
Complete BMSB developmental time studies (lab, screen house), fecundity studies	12/31/2018
Develop, assess alternative degree-day phenology models for forecasting	12/31/2018
Complete comprehensive overwintering & summer phenology models; interface with Activity 3 of this sub-project	8/31/2019
Prepare detailed forecasts and maps of brown marmorated stink bug overwintering potential across Minnesota	5/30/2020
Outcome - Activity 3: Understand the role of climate change on BMSB population dynamics using degree-day and cold-stress models, and assess short-term and long-term impacts	
Use the Weather Research and Forecasting (WRF) model to dynamically downscale climate output from the first set of three global climate change models determined to perform well within the region containing Minnesota for the historical period (1970-1999) and from 2005-2100 for two emission scenarios.	12/31/16
Statistically downscale CMIP5 climate output from 10 CMIP5 models, determined to perform well over both the eastern and middle US. Compare climate analogs between eastern US and MN. Provide data to support Activity 2 of this sub-project, to predict suitability of environment for BMSB.	12/31/2017
Use the Weather Research and Forecasting (WRF) model to dynamically downscale climate output from the second set of three global climate change models determined to perform well within the region containing Minnesota for the historical period (1970-1999) and from 2005-2100 for two emission scenarios.	12/31/2017
Use Weather Research and Forecasting (WRF) model to dynamically downscale climate output from the third set of four global climate change models determined to perform well within the region containing Minnesota for the historical period (1970-1999) and from 2005-2100 for two emission controls.	5/30/2020

Sub-Project Status as of *January 31, 2016:*
The sub-workplan was approved by LCCMR on January 12, 2016. Efforts are now underway to establish a child account and to begin the research.

Sub-Project Status as of *July 31, 2016:*
Good progress has been made with Activity 1, the mobile app to document BMSB sightings to the EDD map system. The project team finds that additional photography of similar common stinkbugs native to Minnesota is needed. A launch date of fall 2016 is anticipated. A post-doctoral associate, Dr. Byju Govindan, was hired in May 2016, to work on Activity 2. Minor changes to the timeline to accommodate the late start are being requested and to gather additional data. The dynamical and statistical downscaling (Activity 3) is making progress; the second post-doctoral associate is hoping to be on-board in early fall 2016. Work at the Minnesota Supercomputing Institute commenced with one historical and future model complete. Finally, Activity 3 has fine-tuned the description of the outcomes and added an additional outcome to better describe this aspect of the project.

Sub-Project Status as of *January 31, 2017*:
This project is making projects under each activity area. The BMSB identification and detection mobile application is near completion and the overwintering and fluctuating temperature studies include both current and future climate scenarios.

Sub-Project Status as of *July 31, 2017:*
Excellent progress was made in all of the activities. Researchers are continued with their analysis of the first year data and conducted additional experiments, relevant to activities one and two. Additionally, the third activity saw progress in the development of the climate models to better understand the future conditions under which BMSB might expand.

Sub-Project Status as of *January 31, 2018:*
The Brown Marmorated Stink Bug (BMSB), *Halyomorpha halys*, is recent invasive species in the U.S. that is native to Asia. BMSB was first detected in the U.S. in the mid-1990s, but was not found in Minnesota until 2010. As with many stink bug species, BMSB has a wide host range, attacking >250 plant species, including many fruit, vegetable and field crops of economic value. The bug is also a severe nuisance pest, as it often invades homes, commercial buildings and other structures during autumn in search of overwintering sites. Given the previous experience of entomologists in the U.S., the primary crops at risk in Minnesota include corn, soybean, sweet corn, tomato, wine grapes, strawberry, and raspberry. Where BMSB has become established, significant increases in economic losses and pesticide use have greatly disrupted crop production. The focus of our project includes three broad objectives: a) development of new monitoring tools for early, consistent detection of BMSB in Minnesota (via new traps and a new app, the "Midwest Stinkbug Assistant") to help farmers, crop consultants and homeowners correctly identify BMSB; b) conduct new studies of BMSB population dynamics and develop forecasting models, to understand how and where this pest is invading and colonizing the state; e.g., to determine the number of generations per year relative to the onset of winter; and c) to compare validated forecasting models of BMSB to current and future climate conditions. Advancements in each of these areas will contribute to improved management programs while minimizing unnecessary insecticide use.

Sub-Project Status as of *July 31, 2018*:
During the past 6-month period, substantial progress continued overall, and primarily for Activities 1-2. For Activity 1, use of the new Dual-lure system for BMSB, continued to provide early spring trap catches of adults – this year by mid-April, which has been predicted by the early Degree-day models (Rutgers; Ann Nielsen et al). These results have also been confirmed with our MDA collaborators (i.e., Angie Ambourn) in Minnesota. The dual lure and sticky trap system is also working well, and was verified by another multi-state, national USDA project that one of us (Hutchison) is collaborating with. Another significant outcome for this activity was the completion of Version 1.0 for the BMSB App. This was completed, following a new collaboration with Purdue University, initiated in 2017; the app was

publically released in April, 2018, with several media outlets providing additional marketing help with numerous popular press articles (including MN Soy Newsletter, AG-WEB, etc.).
Activity 2 was again led by Post-doctoral Assoc. Byju Govindan, and substantial progress was made in analyzing data from all population, life table studies for egg-adult developmental time, survival and fecundity (egg-lay). Our analysis, with 2 years of data, suggests that BMSB (using the MN-acclimated strain) has the ability to complete a partial the 2nd generation (F2) faster than the 1st (F1) in terms of degree-days (DD >14.2C; also known as the "heat units" necessary for insects to complete development. The average DD requirement, using the previously published threshold of 14.2C (Nielsen et al. 2008), indicated DDs necessary for development from egg-adult averaged 544.2 for the 1st generation (very similar to Nielsen et al), but only 411.4 for the 2nd generation. We also checked for the possibility of a statistical artifact in how DDs are calculated, but using the sine-wave model, this was not an issue. Also, one of our lab studies is supportive of this; when BMSB were held at 27C (constant), egg-adult development was faster for the MN-acclimated BMSB vs. published results from PA (Nielsen et al.), i.e., with the MN bugs requiring 80 fewer DDs to complete development (could be 5-12 days under field conditions). However, the "down-side" of this partial generation, is that only about 12 to 18% of the late (5th) instar nymphs were able to molt to the adult stage, and thus have the ability to overwinter (only adults can overwinter successfully). This is due to the gradual cooling from Sept 15 to Oct 15, where fewer degree-days (or heat units per day) are available to the insects to reach maturity. There are interesting trade-offs for this species as it continues to adapt to this northern "edge" of its known range. We are still analyzing the volumes of data to better understand this, and indeed this will be one of the questions we can ask with the more detailed simulation model of BMSB dynamics. Byju has made very good progress in completing a BMSB model, and this will soon be coupled with the climate change models from Dr. Snyder's group (Activity 3), in 2018-2019.

Regarding Activity 3, less productivity was achieved, due to delays in moving the large climate data bases to a new server. These issues will be resolved during the next 6 month period this fall, 2018. Finally, the team participated in several outreach activities with farmers and crop consultants.

Sub-Project Status as of *January 31, 2019*:
During the past 6-months, excellent progress continued with all three activities. For Activity 1, the new Dual-lure/panel trap system for BMSB provided much earlier dates of first catch (May 14th) than the pyramid trap in previous years (usually mid-June). These results were pooled with data from 18 other states for a journal publication. In brief, we observed a major increased in the total numbers of BMSB's captured in 2018 – from 307 BMSB in 2017 to 1,637 in 2018; BMSB has now been detected in 19 counties. The results have also been confirmed with our Minn. Dept. of Agric. collaborators (i.e., Angie Ambourn). In addition to our trapping data, the new Midwest Stinkbug App (see Star Tribune web link) was downloaded by ~588 users as of Nov. 2018.

Activity 2 was again led by Post-doctoral Assoc. Byju Govindan, and progress continued with analyzing data from all screen-house ("tents" for ambient temperature exposure), and lab-based developmental time studies for egg-adult development, and fecundity (egg-lay). Our analysis suggests that the MN-acclimated BMSB strain has the ability to *complete a partial the 2nd generation* (F2) faster than the 1st (F1) in terms of degree-days (DDs, also known as "heat units" necessary for insects to complete development). At least one trade-off has been identified in these studies, which is useful in understanding the ongoing adaptation of BMSB under MN conditions. First, the additional heat (DDs) that can occur in MN summers, can lead to faster developmental times of the summer generation. Secondly, however, warmer temperatures (e.g., >86F), will result in reduced egg-lay by surviving females by ~25%. Taken together, the proportion of eggs laid by summer females, results in about 1.9-15.5% reaching the adult stage in autumn –those that can successfully overwinter. The results have profound implications in altering the BMSB population dynamics on crops in a changing climate. This work has led

to the development of new DD forecasting model for 2019 that will be released in the spring of 2019, via several Extension IPM web sites, including VegEdge and FruitEdge, for commercial growers. The process-oriented, detailed population modeling work is underway, and scheduled for completion in 2019.

Activity 3 outcomes, led by Drs. Snyder and Twine, are now complete except for Outcome 2, the statistical downscaling of climate model data. This includes dynamically downscaling 9 climate models for four time periods – a historical period, and near, mid, and late century projections for two emission scenarios. Although we initially had a delay with data processing via the Supercomputer Institute (UMN), the issues have been resolved. Data has all been processed and the modeling group is currently working with the BMSB modeling group to transfer data to them for their simulations. We have begun work on the statistical downscaling efforts (Outcome 2) that are being run over North America at 25-km resolution.

Outreach: Although fewer outreach activities were conducted during the past 6 months, these were substantial, with the Star Tribune article in August 2018, and a new BMSB Pest Profile, significantly revised and updated for farmers, including translations in *Hmong, Spanish* and *Somali.*

Sub-Project Status as of *July 11, 2019:*
Activity 1: all objectives are now complete, including continued additions of the new BMSB infested counties to EDDMaps system; use of the Midwest Stink Bug Assistant app and trap design comparisons completed. Activity 2: all data collection is complete for objectives 1 and 2; data continue to be analysed; 3 manuscripts are in progress, with the first paper to be submitted by end of June. For objective 3, the detailed simulation model is on track for completion during the summer, with simulations compared to global climate change scenarios to begin summer with Dr. Snyder and team. Activity 3: some progress has been made with both dynamical and statistical downscaling of the high-resolution climate and global climate change data sets for Minnesota and the Midwest region, and new climate data will be available this summer to couple with the BMSB simulation model to assess long-term impacts by BMSB. This activity suffered a small setback when the postdoc on the project was called away unexpectedly for three months. Qualified replacement staff could not be identified in this short time. The postdoc has returned and progress on the project has resumed.

Sub-Project Status as of *January 31, 2020:*
During the past 6 months, progress continued for all Activities, including an increase in BMSB trap captures in the state (Activity 1). However, the increase was primarily limited to the 7-county metro region. However, BMSB populations were highest in residential areas, including our long-term monitoring site in Wyoming, MN, where 3 traps captured 107 adults (56.7/trap). Temperature-dependent models of stage-specific development and survival, and female egg-lay were completed (A2), with key results indicating that the MN population has adapted to have a faster developmental rate and higher survival rate, than a previously studied Pennsylvania population (submitted for publication). Regarding use of Global Change Models (GCMs, A3), final bias corrections for the GCMs were conducted to reassess ten simulations (four future scenarios plus one historical scenario for two GCMs). These simulations are now more than 50% complete. We also finished setting up the statistical downscaling framework for the contiguous U.S. Adult overwintering mortality studies were also completed (A4). For the MN-acclimated BMSB, the lowest temperature that does not cause chill mortality, even after a very long, ecologically meaningful period, is estimated at -3.66°C (25.4F). The model also predicted instantaneous mortality to occur at temperatures at or below -12.5°C (9.5F). Key publications and presentations included the value of the dual-lure, sticky panel traps for BMSB (A1: Acebes-Doria, et al. 2019), and a new life table paper submitted (A2: Govindan & Hutchison). The project was also highlighted in a *Star Tribune* front page story (Oct. 26th), where BMSB was referred to as one of the "Big

3" new insect pests affecting fruit, vegetable and/or field crops in MN (Hutchison and Koch were interviewed).

Sub-Project Status as of *July 31, 2020:*
Significant progress was made during the last 6-month period for the project. While Activity 1 was completed in 2019, the MN adult trap catch data were submitted to Dr. Dave Crowder, Wash. State, as part of a national analysis of BMSB spread. Regarding Activity 2 (A2), temperature-dependent models of stage-specific development and survival, and female egg-lay were published in February 2020. This work reflects one of the most detailed life table analyses published to date, providing a strong foundation for building a detailed population model, now in validation mode (A2). One applied outcome is a new Degree-day model, now available to farmers/crop consultants on the *UMN VegEdge* web site. A 2nd paper by Govindan regarding a detailed life history model for BMSB is complete and will soon be ready for journal submission. Finally, a mechanistic model of BMSB is nearly complete; initial model has been verified using field data from the "insect tent" population growth studies (2016-2018). Results confirmed a good match between the model and observed population growth and phenology. Regarding use of Global Change Models (GCMs, A3), this project was completed; data files are available for BMSB simulations for GCM scenarios. Data from the BMSB overwintering study led to an improved cold stress survival model; a paper summarizing the results has been completed, and is now ready to submit for review (A4). The lowest temperature that does not cause chill mortality, even after a long ecologically meaningful period, is estimated at -3.66°C (25.4F). The model predicted immediate mortality to occur at approx. -12.5°C (9.5F). A key publication for this period included the life table analysis (Govindan & Hutchison, 2020); the paper was well received with over 785 full-text views on the journal web site within the first 4.5 months.

Final report summary:
Just prior to the detection of the Brown Marmorated Stink Bug (BMSB) in Minnesota (2010), this invasive pest had caused ~$35million in damage to the apple industry in Pennsylvania and Atlantic coast states. At the time, we knew very little of its biology, how to monitor this pest, how fast it could spread, and to what extent it could damage MN fruit, vegetable and field crops; a total of at least 12 major MN crops are at risk. With this project we were able to achieve several goals. To support early, more efficient detection of BMSB, we helped evaluate a new "Dual-lure" bait and sticky trap, that was a huge improvement over previous traps. Likewise, to better forecast BMSB infestations we developed and tested a "heat-unit" or degree-day model. DD models are based on the fact that insects cannot regulate their body temperature (cold-blooded). The DD model therefore tracks and accumulates daily heat above a threshold (57.2F for this bug), that allows us to predict when adults become active in the spring, and when peak activity occurs. Our DD model was tested for 3 years at Wyoming MN, where we have an active population. We found the model works well for predicting when overwintered adults will emerge in spring and start laying eggs (predicted at 135 DDs), while the observed time for emergence averaged 123 DDs (or +/-3.3 days of predicted). The model also shows that the first summer adults emerge 1100 DDs later, usually by Aug. 1st (the DD model, with 7-day forecasts was made available to growers via the VegEdge web page). With 4 years of data, we found BMSB does not build to high numbers until late summer, Aug 1 to Sept 30. This information is critical for understanding BMSB risk as a concern for many late-season high-value crops (sweet corn, tomatoes, raspberries, apples, wine grapes). Moreover, we found that the MN-acclimated BMSB has a faster developmental rate (egg to adult) and females produce nearly 30-40% more eggs/female than previously studied populations in the eastern U.S. Results from our overwintering study resulted in a cold-stress model, where the lowest temperature that does not cause chill mortality, is ~25F. The model predicted immediate mortality at ~9.5F. Finally, the BMSB modeling data have been combined with the climate change models, summarized by Dr. Peter Snyder's team (Soil, Water & Climate, UMN), to assess BMSB change over time. They used statistical models to downscale data from 9 modern global climate change models and project climate change for

MN in the 21st century for two emissions scenarios. This includes high-resolution datasets (~10 km grid); these datasets will be available for all other MITPPC projects going forward.

SUB-PROJECT 3: Climate Change and Range Expansion of Invasive Plants

Sub-project manager: Dr. David Moeller

Description: The project will develop and validate predictive distribution models of high priority invasive species under current and future climates. This work will improve detection and establish priorities for eradication and management.

Sub-project work plan approval date: January 12, 2016

Sub-project budget: $206,335

Outcome - Activity 1: Predicting invasion under current climate	**Completion date**
Maps predicting current distribution of 11 invasive plant species	6/30/2019
Maps predicting potential distribution of 11 invasive plant species	6/30/2019
Detailed documentation of plant communities associated with 3 invasive species	8/31/2017
Maps predicting potential distribution that incorporates the biotic environment for 3 invasive species	8/31/2017
Outcome - Activity 2: Predicting invasion under future climate change using regional climate projections	
Determination of historical rates of range expansion in relation to climate change from 1970-present	11/30/2017
Maps predicting potential distributions under climate change (2041-2080) for 9 invasive plant species	12/31/2017
Maps predicting potential distributions under climate change using downscaled MN-specific climate predictions	6/30/2018
Outcome - Activity 3: Testing and refining species distribution models using targeted field surveys	
Detection of new populations of 3 invasive plant species in the current geographic area of occupancy	4/30/2017
Recommendations for future surveys beyond the current range of those species	6/30/2019

Sub-Project Status as of *January 31, 2016:*
The sub-workplan was approved by LCCMR on January 12, 2016. Efforts are now underway to establish a child account and to begin the research.

Sub-Project Status as of *July 31, 2016:*
Since funding began in February 2016, a team of researchers including one postdoctoral associate, Ryan Briscoe Runquist, two UMN undergraduate researchers – one from CFANS and one from CBS and a part-time technician, who has expertise in plant collections management have been hired. This team has undertaken the large task of accumulating and processing records of the locations of nine invasive plant species throughout Minnesota, North America, and across the Earth. Thus far, significant strides have been made by developing a computational pipeline by which records are acquired, filtering for data quality, and vetting locality records for future analyses. This process will not only provide essential information for the species distribution models, but will also provide a centralized database for future research and monitoring in Minnesota. In the process of identifying data sources, close interface the Minnesota Department of Natural Resources and the Minnesota Department of Agriculture staffs was critical. Thus far, locality records have been acquired and curated for three invasive plant species: *Celastrus orbiculatus* (Oriental Bittersweet), *Cynanchum louiseae* (Black Swallow-wort), and *Humulus*

japonicus (Japanese Hops). Maps that show the distribution of the locality points for each species (14,395 for *C. orbiculatus,* 2,582 for *C. louiseae,* 1,518 for *H. japonicus*) are given in the update to the associated sub-project workplan. Work was initiated on an additional three species using the newly developed pipeline.

Presentations and Outreach in which our work was discussed
MITPPC Advisory Board Meeting
Meeting with MN DNR (Laura Van Riper and Andy Holdsworth)
Meeting with MN DA (Monika Chandler)
Meeting with an expert on species distribution modeling (Vincent Eckhart)
Presentation to Governor Dayton's staff during a review of funding requests from UMN (including renovation of Moeller and Tiffin laboratory) where research in our labs was described
Presentation to Minnesota Legislators and their staff during a review of funding requests from UMN (including renovation of Moeller and Tiffin laboratory) where research in our labs was described
Sub-Project Status as of *January 31, 2017*:
The project team's main activities refined the computational pipeline for acquiring records, filtering the data quality, and vetting locality records for future analysis. Data was gathered for all invasive plant species being studied. Additionally, plant community surveys were conducted to assist with the distribution models.

Sub-Project Status as of *July 31, 2017:*
Project researchers made significant progress on the building the current climate model for the nine species being studied. The species distribution models (SDMs) will be critical to understanding the areas of greatest possible distribution of these invasive plants. The research team will focus its future efforts on SDMs for future climate conditions.

Sub-Project Status as of *January 31, 2018:*
Invasive plant species are a significant and growing threat to agriculture, the economy, and natural spaces. How we manage these species already has and will continue to have important ecological and economic repercussions, such as the increased use of pesticides and the loss of biodiversity and native habitats. In our project, we are interested in understanding how environmental factors may influence species that are problematic and invasive in the continental United States to expand their ranges into Minnesota. We are building correlative species distribution models using machine-learning techniques for species that are potential invasion threats. The species being investigated include: Palmer Amaranth, Dalmatian Toadflax, Black Swallowwort, Narrowleaf bittercress, Common Teasel, Oriental Bittersweet, Japanese Hops, and Brown Knapweed. To build these models we are using multiple sources of climatological and other sources of environmental data and then using the models to predict the potential suitability of Minnesota habitats for invasion under current climatological conditions and under different future climatological scenarios. In preliminary models of all species, we have found that although there is some small variability among species, areas in Southern Minnesota and some in Central Minnesota are at greatest risk of invasion under current climate conditions and that this result is robust to the use of different climatic datasets and model building techniques. We have also found that predictions of habitat suitability under future climate projections increase for much of Minnesota and more areas of the state are at greater risk of invasion.

Sub-Project Status as of *June 30, 2018*
During the past six months, work was conducted by the core team, including the PIs (Moeller and Tiffin) and a post-doctoral researcher, Ryan Briscoe Runquist (Ph. D., U. California Davis). Our main activity during this period has been to compete model generation and projection for current and future distributions of the eight species within the scope of work (Grecian Foxglove was excluded due to the

paucity of records). For all species, we explored the variation in model building techniques; we incorporated information about species spread and spatial autocorrelation; we also generated markdown documents with code to regenerate the models and projections or for use in future analyses of other species. Using our models, we have projected current and future distributions for all eight species. For future climates, we downloaded and processed data for 2050 and 2070 for 5 GCMs (CCSM4, GFDL-ESM2G, IPSL-CMSA-LR, MIROC-ESM, and MRI-CGCM3) that performed well for North America when assessed by CMIP5. We have also generated joint species distribution models for three species in MN using the detailed DNR releve data. During this period, we finished a manuscript on Palmer Amaranth and submitted it for peer review to Biological Invasions and are awaiting a decision. We have also begun to prepare a manuscript that included the other SDMs and JSDMs with current plans to submit to Diversity and Distributions. We have also begun to prepare guidelines on how to interpret findings for projections into MN. Two additional species were added to this research and work began to gather initial data necessary to build the SDMs.

Sub-Project Status as of *January 31, 2019:*
In the past six months, the core team, including the PIs (Moeller and Tiffin) and a post-doctoral researcher, Ryan Briscoe Runquist (Ph. D., U. California Davis) and a new graduate student in the UMN Plant and Microbial Biology Graduate program, Thomas Lake, have continued to prepare products for presentation and have met the project outcomes for the past six months. The team's first publication has been accepted for publication in the open-access journal, *Scientific Reports*. The paper is titled "Species distribution models throughout the invasion history of Palmer amaranth predict regions at risk of future invasion and reveal challenges with modeling rapidly shifting geographic ranges". This publication is peer-reviewed and will be freely available for the scientific and management communities. Dr. Briscoe Runquist also presented the results of this paper at the UMISC meeting in MN this past October. Additionally, we are preparing two additional manuscripts for publication in academic journals and preparing a document with Minnesota-specific species distribution projections for use by management professionals. The academic publications will include the current and future projections for all of the species in the scope of work and investigations of methodological considerations for predicting invasion risk. The management document, which is currently in preliminary draft form and being revised, will be made available through the MITPPC and will present assessments of potential invasion risk for areas of Minnesota under current and future climate conditions.

Sub-Project Status as of *July 11, 2019:*
Over the last six months, the project team has completed all of the goals and objectives as laid forth in our original proposal, "Climate change and range expansion of invasive plants", as well as the aims of the amendment to our proposal starting in July 2018. We have successfully produced invasive species models for the ten species for which we were able to attain reliable data and projected the models into current and future climates in Minnesota. We have produced a PDF document that presents our model projections and interpretation of potential habitat suitability for all of the species. This document can be used by the MITPPC and other agencies and stakeholders within Minnesota and the Upper Midwest when trying to assess climate related risk for the species of interest. Our first publication from the project, "Species distribution models throughout the invasion history of Palmer amaranth predict regions at risk of future invasion and reveal challenges with modeling rapidly shifting geographic ranges", was published in the open access journal, *Scientific Reports*. This work was also presented as a poster at the Palmer Amaranth conference held in January 2019 by the MITPPC. We are currently preparing two additional manuscripts for submission by late summer/early fall on the SDMs for the remaining nine species. The project has not met any major obstacles over the past six months.

Final report summary:

In our project, 'Climate change and range expansion', our goal was to use public records of species presences and available environmental data to build models that predicted the habitat suitability and invasion risk under current and future climate scenarios for 10 invasive species of interest to MN. Those species were: Common Tansy, Wild Parsnip, Palmer Amaranth, Oriental Bittersweet, Narrowleaf Bittercress, Japanese Hops, Common Teasel, Dalmatian Toadflax, Brown Knapweed, and Black Swallowwort. We originally planned to include Grecian Foxglove, but were unable to obtain enough data to build reliable models. We developed species distribution models (SDMs) using multiple techniques (Maxent, Boosted Regression Trees, and Joint Distribution Modeling of Communities) and multiple scales (North American continent and Upper Midwest) to validate results. We wrote a report with detailed finding from our SDMs titled, "Species Distribution Model Projections for Incipient Invasive Species of Minnesota". Our findings can be used to help guide management decisions about surveillance and eradication efforts for these species. Additionally, we have published on our findings on methods for producing accurate models of invasive species and specific SDMs for the species of interest in academic peer-reviewed journals. We have also presented our work at the UMISC-NAISMA and Palmer Amaranth Conferences and have participated as presenters in USFS land manager training. The project supported or trained one postdoctoral scholar, one postgraduate research assistant, two undergraduate students, and one graduate student. One undergraduate student decided to continue as a graduate student working on invasive species and is an author on all of the manuscripts and data products. The management document and all of the underlying data, models, and projections are archived at the Data Repository for U of M (DRUM) and are freely available to Minnesotans to access to gain a better picture of the potential distributions of the listed species.

SUB-PROJECT 4: Cover it Up! Using Plants to Control Buckthorn
Project manager: Dr. Peter Reich
Description: Management tools will be developed to limit buckthorn re-colonization following its removal, by identifying cost-effective methods of establishing dense cover of preferred plant species that will suppress buckthorn regeneration.
Sub-project work plan approval date: January 20, 2016
Sub-project budget: $327,000

Outcome - Activity 1: Pairing non-mechanical buckthorn removal with post-removal seeding and planting to suppress buckthorn recovery	**Completion date**
Census performance of buckthorn, planted species, and native volunteers	8/31/2016
2. Statistical analyses and publication-ready manuscripts completed	2/1/2019
Outcome - Activity 2: Pairing mechanical buckthorn removal with post-removal treatments	
Identify and establish sites and plots	11/30/2016
Plant seeds and juveniles in all plots	7/31/2017
Census performance of buckthorn, planted species, and native volunteers	6/30/2018
Statistical analyses and publication-ready manuscripts completed	12/31/2019
Outcome - Activity 3: Testing buckthorn response to dense plantings of juvenile trees	
Plant seeds and seedlings in all plots	6/30/2017
Census performance of buckthorn, planted species, and native volunteers	7/31/2018
Statistical analyses and publication-ready manuscripts completed	8/31/2018

Sub-Project Status as of *January 31, 2016:*
The sub-workplan was provisionally approved by LCCMR on January 20, 2016. Additional details are being provided to LCCMR about the use of funds for Equipment/Tools/ Supplies. Efforts are now underway to establish a child account.

Sub-Project Status as of *July 31, 2016:*
Two post-doctoral associates were hired in May 2016, Drs. Peter Wragg and Michael Schuster, and have begun the experimental research, including data analysis and publication writing. Given the late hiring date, activity timelines will need adjusting and outcomes reordered and a minor change in the budget, shifting funds from personnel to travel. Additionally, after careful survey of research plots, changes were made to the seeding and planting activities and timing at a few of the sites. Principle investigators believe that these small changes greatly improve the rigor of the research findings.

Sub-Project Status as of *January 31, 2017*:
The research team surveyed established buckthorn sites, planted species, and volunteers in two experimental plots. The team also identified sites for experimental plots and planted buckthorn seedlings at one site in northern Minnesota.

Sub-Project Status as of *July 31, 2017:*
All project objectives are progressing according to schedule. Statistical analyses for Activity 1 are ongoing. Field activities for Activity 2 with summer 2017 completion dates have been completed and measurements pertaining to Activity 2 have commenced. A new cohort of seeds were planted at the IDENT experiment for Activity 3 and measurements of last year's seedlings and resource availability are ongoing.

Sub-Project Status as of *January 31, 2018:*
Common buckthorn is an invasive shrub or small tree that displaces native plants, degrades wildlife habitat, and inhibits human use of forests. In Minnesota alone, millions of dollars are spent each year to remove buckthorn and restore affected areas. However, many efforts to remove buckthorn only yield temporary relief because removing buckthorn creates an ecological vacuum that is often more easily filled by buckthorn than by native species. Cover It Up aims to develop strategies that increase the abundance and diversity of native plants and enhance forests' ability to prevent buckthorn from coming back after it has been removed. In partnership with over a dozen public, private, and non-profit organizations, we are testing the ability of diverse mixtures of native species to suppress buckthorn in areas where buckthorn has been removed. At each of six experimental sites around Minneapolis/Saint Paul, we seeded large plots with a mixture of 35 grass and wildflower species in February 2017. Since then, we have been monitoring the performance of buckthorn and native species both with and without follow-up herbicide treatment of buckthorn. Additionally, we are monitoring the performance of buckthorn in smaller plots planted with either a mixture of four shrub species, a Maple-Fir mixture, sedges, or ferns. This work, combined with our monitoring of buckthorn in existing forest experiments, has already characterized how deep shade can slow buckthorn growth, and will provide further insights into the effectiveness of using native plants to suppress buckthorn in the coming years.

Sub-Project Status as of *July 31, 2018*:
All project objectives are progressing according to schedule. Soil analyses for Activities 1 and 2 were completed in spring 2018. Work is proceeding on statistical analyses and a manuscript for Activity 1. Field activities for Activity 2 (maintaining experiments and measuring effects of planting and planting plus herbicide treatments on buckthorn regeneration) are ongoing. One manuscript based on Activity 1 and two manuscripts based on Activity 2 are in progress. For Activity 3, measurements of buckthorn growth in varying light levels are ongoing; statistical analyses are at an advanced stage and a manuscript is in preparation. Two students were hired to assist with measurements May-August 2018.

Sub-Project Status as of *January 31, 2019*:
All project objectives are progressing according to schedule; we have requested a six month no-cost extension until December 30, 2019 to complete analysis and writing about this research project. A manuscript detailing the conclusions of Activity 1, led by Wragg, is undergoing internal review. Extensive field work associated with Activity 2 concluded in November 2018 and three manuscripts detailing the findings of that activity are in preparation (one led by Wragg and two led by Schuster). Measurements of buckthorn performance in Activity 3 concluded in October 2018 and a manuscript detailing the findings of that activity, led by Schuster, is undergoing internal review. A paper evaluating the existing research on revegetation efforts like those being tested by Cover It Up, led by Schuster, was published in the Journal of Applied Ecology. The research team made presentations to over 500 people throughout the past six months.

Sub-Project Status as of *July 11, 2019*:
All field and lab work has been completed according to schedule. A manuscript detailing the conclusion of Activity 1, led by Wragg, is ready for submission. Four manuscripts arising from Activity 2 are in various stages of preparation: a manuscript led by an undergraduate intern (Anfang) is ready for submission and another led by Wragg is nearing completion. Two additional manuscripts based on data collected during Activity 2 (herbicide efficacy and phenology) are planned for the near future to be led by Schuster. A manuscript detailing findings from Activity 3 led by Schuster is ready for submission. The research team attended the Gathering Partners Conference in May 2019 and is preparing experimental sites for continued and expanded experimental work as part of a new MITPPC-funded grant (ML 2016, Chp. 186, Sec. 2, Subd. 06a.)

Sub-Project Status as of *January 31, 2020:*
This project has concluded and all objectives have been met according to schedule. Over the past 6 months, work has focused on preparing and submitting manuscripts. Four publications have been submitted to academic journals during this time.

Final report summary:
Buckthorn is an invasive shrub that outcompetes native plants and degrades Minnesota forests. Removal of buckthorn is a common management activity but often only provides short-lived benefits since buckthorn rapidly re-establishes. In grasslands, heavily seeding native species can often restore native communities and inhibit invasion, but this approach is rarely used in forest management (Schuster et al. 2018). We investigated whether we could similarly establish enough native plants to prevent buckthorn from re-establishing in forest using three separate experiments.

First, we surveyed sites at 24 properties in Minnesota where buckthorn management had taken place to identify the most successful techniques (Wragg et al. in review). Management success was highly variable, but sites where more native vegetation had been re-established tended to have lower buckthorn abundance.

Second, we measured the growth and survival of buckthorn seedlings in a forest biodiversity experiment. There, we found that canopies that permitted less than 10% of incoming light had significantly reduced buckthorn growth and canopies that permitted less than 3% light, particularly in the spring and fall, completely excluded buckthorn (Schuster et al. 2020).

Third, we established a series of experiments across 7 sites that had recently had buckthorn removed. In those experiments, we tested how densely seeding or planting native plants affected buckthorn seedlings. After 3 years, we found that planting trees and shrubs, particularly *Sambucus* shrubs, greatly reduced light levels and excluded buckthorn (Wragg et al., Schuster et al. in prep). Other seeding and planting treatments had more moderate effects and may require additional years to

become fully effective. We also found that the rarely-used herbicide fosamine ammonium was effective at controlling buckthorn (Schuster et al. in review).

The Cover It Up! project illustrates that it is possible to curate native plant communities in a way that makes them resistant to buckthorn invasion. In general, we recommend that forests be managed to promote the establishment of shrubs and trees that provide heavy shade in the spring and fall. Our findings suggest that by doing so, managers can simultaneously increase forest health, inhibit invasion, and reduce the need for investment in future buckthorn removals.

SUB-PROJECT 5: Terrestrial Invasive species prioritization
Project manager: Dr. Amy Morey
Description: This project will solicit additional TIS to consider in the prioritization. This research project will add assessments for 12 TIS threats to Minnesota to the statewide prioritization. The information will be incorporated into the next regular update of invasive species priorities for MITPPC (to be issued in January 2022). Additionally, this project will evaluate the current prioritization methodologies with other robust platforms to determine the best for TIS management needs.

Sub-project work plan approval date: 12/09/2020

Sub-project budget: $32,000

Outcome - Activity 1: TIS evaluations	**Completion date**
Six TIS evaluations completed (12 total)*	10/31/2020
Methods of threshold modelling determined and one preliminary model produced	10/31/2020
Updated prioritization of 210 species	1/31/2109
Risk maps based on threshold models constructed and compared to existing MaxEnt models for at least four TIS	1/31/21

*Tentative list of species to be evaluated:
Candidatus phytoplasma pini 16SrXXI-A (pine witches broom)
Candidatus phytoplasma solani 16SrXII-A (bois noir - black wood)
Candidatus phytoplasma ulmi (elm yellows)
Candidatus phytoplasma vitis 16SrV-C (flavescence doree of grape)
Rosa multiflora (multiflora rose)
Poa pratensis (Kentucky bluegrass)
Vibernium opulus subsp. opulus (European high cranberry)
Lythrum salicaria/virgatum (purple loosestrife)
Mycosphaerella gibsonii (brown needle blight of pine)
Ulmus pumila (Siberian elm and hybrids)
Xanthomonas populi pv. populi (bacterial canker and dieback)
Fallopia (knotweed hybrids)

Sub-project Status as of *January 31, 2021*
All deadlines and goals expected of the updated species prioritization project from June 1 – Dec 1, 2021 were met. No significant obstacles were encountered. The results of this work will provide an updated prioritization of species for an anticipated 2021 funding cycle. This process allows the MITPPC to be dynamic and transparent in how it responds to emerging TIS threats and stakeholder concerns. In addition, a manuscript of a technical description of the MITPPC prioritization process was submitted and accepted for publication (pending revisions). This document will enable the MITPPC prioritization

process to be more visible to the scientific and pest management communities. Lastly, the project lead (A. Morey) was co-author to an oral and poster presentation on MITPPC research given at a conference in Oct. 2020.

Final report summary:
In 2017, the Minnesota Invasive Terrestrial Plants and Pests Center undertook an expansive research prioritization to systematically evaluate threats posed by a wide array of terrestrial invasive invertebrates, plants, and plant pathogens and created the document, "*Minnesota's Top 124 Terrestrial Invasive Plants and Pests: Priorities for Research*," which has provided guidance on funding MITPPC research projects in subsequent years. Since its publication, many terrestrial invasive species (TIS) have been suggested for further review by stakeholders. The movement of TIS into Minnesota and their potential harms calls for a thorough review of suggested species.

Following methodology developed in the 2017 document, this MITPPC project evaluated 12 TIS submitted for review. The evaluations are incorporated into the Analytic Hierarchy Process (AHP) model used by MITPPC to rank and prioritize the TIS that threaten Minnesota's terrestrial ecosystems. AHP is a form of multi-criteria decision analysis that makes the process of selecting the highest priority threats consistent and transparent. AHP has been used by many agencies and organizations to facilitate complex decision-making. Evaluations from this project will be incorporated into the 2022 update of MITPPC research priorities. In addition, a process for soliciting stakeholder TIS review requests was outlined and provided to MITPPC leadership for future consideration. The process is intended to encourage systematic and transparent solicitation of TIS of concern from stakeholders.

Initial plans for the project also involved comparing methods of climate suitability modeling for TIS to identity a method most useful in MITPPC evaluations. In consultation with MITPPC leadership, the project instead focused on writing a formal and more detailed description of the MITPPC prioritization process outlined in the 2017 whitepaper. The manuscript was submitted and accepted to a scientific journal. The forthcoming publication will be an important resource for communicating the transparency and rigor of MITPPC research priorities.

V. DISSEMINATION:

Description: Findings will be shared with agencies and citizen groups so that public information and decision making is based on the best available science. Updates on progress and research results will be disseminated through University of Minnesota, College of Food, Agricultural, and Natural Resource Sciences, and College of Biological Sciences via websites, social media, and publications. Media releases will also be used when warranted. Additionally, findings will be presented at local and national conferences and via peer-reviewed publication and student theses.

Status as of *January 31, 2015*:
Nothing to report.

Status as of *June 24, 2015***:**
A website and a Google group have been established for the MITPPC. Both may be accessed at www.mitppc.umn.edu. The website is intended to provide updates about planned and achieved progress of the Center, to announce RFPs and awards of grants, and to publicize research results. The website will assist a general educational function by publicizing pertinent media releases concerning terrestrial invasive species. The website will also provide process transparency for participants and

stakeholders interested in these issues. The Google groups are intended to facilitate communications with our Center Faculty Group and other stakeholders external to the University.

Status as of *December 1, 2015*
Presentations delivered about the Minnesota Invasive Terrestrial Plants and Pests Center:
University of Minnesota, College of Food, Agricultural, and Natural Resources Sciences. Graduate and Research Policy Review Committee. St. Paul, MN. Feb 27, 2015.
Minnesota State Legislature. Senate Hearings. St. Paul, MN. March 26, 2015.
University of Minnesota, Department of Plant Pathology. St. Paul, MN. March 27, 2015.
Minnesota Invasive Species Advisory Council. Shoreview, MN. April 22, 2015
University of Minnesota, College of Food, Agricultural, and Natural Resources Sciences, Faculty Consultative Committee. St. Paul, MN. April 30, 2015.
University of Minnesota, College of Food, Agricultural, and Natural Resources Sciences.
College Assembly. St. Paul, MN. May 12, 2015.
University of Minnesota, Research and Outreach Center. Grand Rapids, MN. June 16, 2015.
Terrestrial/Aquatic Invasive Species Extension Staff Development. Minnesota Extension Service. Chaska, MN. August 12, 2015.
Center Advisory Board, Minnesota Invasive Terrestrial Plants and Pests Center. St. Paul, MN. September 21, 2015.
Minnesota Invasive Species Advisory Council. Shoreview, MN. Oct 21, 2015.
Minnesota Department of Agriculture, Plant Protection Division. St. Paul, MN. October 23, 2015.

Status as of January 31, 2016:
Presentations delivered about the Minnesota Invasive Terrestrial Plants and Pests Center:
Minnesota Forest Resources Partnership, Brainerd, MN. December 17, 2015
Research Review 2016, Cloquet Forestry Research and Outreach Center, Cloquet, MN. January 12, 2016
DNR Roundtable. Brooklyn Center, MN. January 15, 2016

Status as of July 31, 2016:
During this reporting period, the MITPPC redesigned its website (mitppc.umn.edu) and established a Twitter (@umnmitppc) to its social media complement. The center also added Google analytics to better understand its website audience.

Presentations delivered about the Minnesota Invasive Terrestrial Plants and Pests Center:
Lessard-Sams Outdoor Heritage Council. February 11, 2016
The Nature Conservancy. March 4, 2016
MNDNR Wildlife section leaders. March 7, 2016
Great River Greening. March 14, 2016
Pheasants Forever. March 16, 2016
CFANS Research Fair. March 23, 2016
Shakopee Mdewankanton. April 5, 2016
Friends of the Mississippi River. April 5, 2016
MN House of Representatives, Environment and Natural Resources Policy and Finance committee. April 20, 2016
Dr. Sally Rockey, Director, USDA's Foundation for Future Agricultural Research. April 25, 2016
Radio interview with WTIP (Grand Marais, MN); July 18, 2016. Archived at http://www.wtip.org/node/31
Minnesota Landscape Association. July 26, 2016
Minnesota Invasive Species Advisory Council. July 27, 2016.

Status as of January 31, 2017:
Presentations delivered about the MITPPC include:
Upper Midwest Invasive Species Conference, October 17-19, 2016
Soybean aphid and prairie butterfly symposium, November 15, 2016
LCCMR presentation, November 15, 2016
Soybean Growers Association, November 18, 2016
UMN Research and Outreach Center faculty retreat, November 22, 2016

Status as of July 31, 2017:
Presentations delivered about the MITPPC and terrestrial invasive species include*:*
Minnesota House of Representatives Agriculture Finance Committee, February 23, 2017
Unite States Forest Service presentation, March 1, 2017
Emerald Ash Borer Workshop, May 23, 2017
Legislative Citizen Committee on Natural Resources, June 7, 2017
Minnesota Soybean Growers and Promotion Council meeting, July 25, 2017
Emerald Ash Borer Researchers conference, July 25, 2017

Status as of January 31, 2018:
Presentations delivered about the MITPPC and terrestrial invasive species include:
UMN North Central Research station, August, 24, 2017
Legislative Citizen Committee on Natural Resources, October 17, 2017
Rebecca Swenson agricultural communications class, October 30, 2017
Buckthorn symposium, November 14, 2017
Women in Agriculture, November 17, 2017

Status as of July 31, 2018:
Presentations delivered about the MITPPC and terrestrial invasive species include:
Venette, R.C.; and Aukema, B.H. 2018. The future of forest pests. St. Croix Forestry Association. Sandstone, MN. February 28, 2018. (Invited co-presentation).
Venette, R.C. 2018. Terrestrial invasive species: moving forward together. ESPM 2021 – Environmental Sciences: integrated problem solving. University of Minnesota. St. Paul, MN. March 29, 2018. (Invited guest lecture).
Venette, R.C. 2018. Terrestrial invasive species. National Advanced Silviculture Program. St. Paul, MN. April 12, 2018. (Invited online lecture).
Venette, R.C; Palik, B.; Handler, S.; Montgomery, R.; Schneider, I.; and Snyder, S. 2018. Terrestrial invasive species. Minnesota Forest Resources Council – Research Advisory Committee. St. Paul, MN. May 10, 2018. (Invited presentation).
Venette, R.C.; Reich, P.B.; Schuster, M.; and Kee, D. 2018. Cover It Up! Using plants to control buckthorn. Legislative-Citizen Commission on Minnesota Resources. St. Paul, MN. June 5, 2018. (Invited co-presentation).

Status as of January 31, 2019:
Dissemination directly by MITPPC:
Presentations:
Cira, T.; Hutchison, W.D.; Pezzini, D.; Koch, R.L.; and Venette, R.C. 2018. Midwest stink bug assistant. University of Minnesota-Extension, Invasive Species Community of Practice. West Central Research and Outreach Center, Morris, MN. September 18, 2018.
Venette, R.C.; and Koop, H. 2018. Priority invasive pests for Minnesota's forests and strategic research investments. 2018 Joint Meeting of the Upper Midwest Invasive Conference and the North American Invasive Species Management Association. Rochester, MN. October 15, 2018.

Venette, R.C.; Christianson, L.; and Abrahamson, M. 2018. Polar plunge for emerald ash borer: is there a place that is too cold. 2018 Joint meeting of the Entomological Society of America, the Entomological Society of Canada, and the Entomological Society of British Columbia. Vancouver, BC. November 13, 2018. (ENRTF funding was not used to pay for this trip.)
Venette, R.C. 2018. MITPPC & weeds: ongoing and upcoming research. Noxious Weed Advisory Committee to the Minnesota Department of Agriculture. Arden Hills, MN. December 19, 2018.
Relaunch of MITPPC's website on January 15. Visit https:mitppc.umn.edu.
Development of brochure "Minnesota Invasive Terrestrial Plants and Pests Center: Spotlight on Soybeans." Distribution of 200 copies (100 requested by Minnesota Soybean Research and Promotion Council).

Sub-project #1:
No activity for sub-project 1.

Sub-project #2:
Presentations:
Govindan, B.N.; Hutchison, W.D.; Koch, R.; Twine, T.; Snyder, P.; and Abrahamson, M. 2018. Life-table studies and modeling time-temperature relationships in cold-induced mortality of the brown marmorated stink bug (*Halyomorpha halys*). 2018 Joint Meeting of the Upper Midwest Invasive Conference and the North American Invasive Species Management Association. Rochester, MN. October 17, 2018.
Public relations:
"Keep an eye out for the brown marmorated stink bug, and yes, there's an app for that" –Minneapolis, Star Tribune article, Aug. 18, 2018.
http://www.startribune.com/keep-an-eye-out-for-the-brown-marmorated-stink-bug-and-yes-there-s-an-app-for-that/491132461/

Wold-Burkness, S. & W.D. Hutchison. 2018. Brown Marmorated Stink Bug—Pest Profile (updated, Dec. 2018) https://www.fruitedge.umn.edu/bmsbpp

Hutchison, W.D. & S. Wold-Burkness. 2018. Brown Marmorated Stink Bug—Pest Profile (updated, Dec. 2018) https://www.fruitedge.umn.edu/bmsbpp *(Also translated to: Hmong, Spanish, Somali)*
Sub-project #3:
Publications:
Briscoe Runquist RD, Lake T, Tiffin P, Moeller DA. 2018. Species distribution models throughout the invasion history of Palmer amaranth predict regions at risk of future invasion and reveal challenges with modeling rapidly shifting geographic ranges, *Scientific Reports, in-press*
Manuscript *in-prep* to include current and future projections for: Black Swallowwort, Common Teasel, Brown Knapweed, Dalmatian Toadflax, Common Tansy, and Wild Parsnip. This effort is being led by Thomas Lake with support from Dr. Briscoe Runquist and Dr. Moeller.

Manuscript *in-prep* to include current and future projections and JSDMs for: Oriental Bittersweet, Japanese Hops, and Narrowleaf Bittercress. This effort is led by Dr. Briscoe Runquist.

Presentations:
Species Distribution Models of Multiple Stages of Invasion in Palmer amaranth (*Amaranthus palmeri*), *UMISC presentation, R. Briscoe Runquist*
Conversation with Kelsey Wenner, IS coordinator of the Fond du Lac Band of Lake Superior Chippewa, December 2018

Sub-project #4:
Publication:
Schuster, M.J., Wragg, P.D. & Reich, P.B. (2018) Using revegetation to suppress invasive plants in grasslands and forests. Journal of Applied Ecology, 55, 2362-2373.
Presentations:
Upper Midwest Invasive Species Conference (October 2018). Oral presentations by Schuster and Wragg (approx. 100 attendees each) and one poster presentation by research technician Anfang.
Saint Croix River Research Rendezvous (October 2018). Oral presentation by Wragg (approx. 100 attendees) and poster presentation by Anfang.
Metropolitan State University Natural Sciences Department seminar (October 2018). Oral presentation by Wragg (approx. 30 attendees).
Hamline University Intro to Biology (September 2018). Oral presentation by Schuster (approx. 60 attendees).
CitSciMN symposium (November 2018). Discussions with Schuster (approx. 30 interactions).
Marine Community Library (November 2018). Oral presentation by Reich (approx. 160 attendees).

Status as of July 11, 2019:
Dissemination directly by MITPPC:
Presentations:
Roundtable discussion with Rep. Betty McCollum, January 18, 2019. University of Minnesota, St. Paul, MN.
Roundtable discussion with Sen. Tina Smith, January 22, 2019. University of Minnesota, Minneapolis, MN.
Venette, R.C. 2019. Cold enough for you, EAB?!? Webinar sponsored by the Minnesota Department of Agriculture. March 4, 2019. St. Paul, MN.
Venette, R.C., H. Koop, & A.C. Morey. Clarity, consistency, and concern: communication in support of an invasive species research center. Invited presentation in symposium "Niche Specialization: Communicating Science to Targeted Audiences". 74th North Central Branch meeting of the Entomological of Society of America. Cincinnati, OH. March 19, 2019. [presented by A.C. Morey; travel not funded by ENRTF].
Venette, R.C. 2019. MITPPC: Research progress on invasive species. Quarterly meeting of the Minnesota Invasive Species Advisory Council. April 11, 2019. Shoreview, MN.
Roundtable discussion with Rep. Betty McCollum and national US Geological Service Director James Reilly. April 15, 2019. University of Minnesota, St. Paul, MN.
Venette, R.C. 2019. Terrestrial Invasive Species: Impacts on Water. Clean Water Council, June 17, 2019. St. Paul, MN.
Venette, R.C. 2019. A center for research on terrestrial invasive species. Genetic biocontrol of invasive species working group meeting. June 25, 2019. St. Paul, MN.
Venette, R.C. & H. Koop. 2019. Minnesota Invasive Terrestrial Plants and Pests Center (MITPPC): Phase 5. Legislative Citizen Commission on Minnesota Resources. June 26, 2019. St. Paul, MN.

Sub-project #1:
No activity during this reporting period.

Sub-project #2:
Publications:

June, 2019: (Activity 1), As part of our research to evaluate improved traps and lures for BMSB monitoring (led by Eric Burkness), we leveraged the results of other states, resulting in the following multi-state publication, submitted for review:

Acebes-Doria, A.L., A.M. Agnello, B.R. Blaauw, G. D. Buntin, D.G. Alston, E.H. Beers, J.C. Bergh, T.E. Cottrell, R. Bessin, S. Chen, K.M. Daane, S.Fleischer, C. Guédot, L.J. Gut, G.C. Hamilton, R.Hilton, K.A. Hoelmer, E.C. Burkness, W.D. Hutchison**,** et al. Season-long monitoring of the Brown Marmorated Stink Bug, *Halyomorpha halys* Stål (Hemiptera: Pentatomidae), throughout the United States using commercially available traps and lures. *Journal of Economic Entomology*. (submitted, 6-4-19).

Presentations:
Upper Midwest Fruit & Vegetable Growers Meeting, MN Fruit & Veg. Growers Annual Meeting (January 2019.) MN Extension IPM Team, with Hutchison graduate students, hosted an IPM Trade Show exhibit to display live BMSB adults/nymphs to farmers and agric. crop consultants; over 2 days, ~60 growers at exhibit.
First BMSB Degree-day (heat accumulation) forecast model released for farmer, crop consultant use, as early-warning system for stink bug adult emergence from overwintering, and subsequent start of egg-lay in spring (May 2019.) The DD model is one of a suite of insect model forecasts now available at the UMN VegEdge web page: https://www.vegedge.umn.edu/bmsbdd

Sub-project #3.
Publications:
Briscoe Runquist, R.D., T. Lake, P. Tiffin, and D.A. Moeller. 2019. Species distribution models throughout the invasion history of Palmer amaranth predict regions at risk of future invasion and reveal challenges with modeling rapidly shifting geographic ranges. Scientific Reports 9: 2426
Manuscript *in-prep* to include current and future projections for: Black Swallowwort, Common Teasel, Brown Knapweed, Dalmatian Toadflax, Common Tansy, and Wild Parsnip. This effort is being led by Thomas Lake with support from Dr. Briscoe Runquist and Dr. Moeller.
Manuscript *in-prep* to include current and future projections and JSDMs for: Oriental Bittersweet, Japanese Hops, and Narrowleaf Bittercress. This effort is led by Dr. Briscoe Runquist.

Sub-project #4:
Presentations:
MITPPC Advisory Board Meeting, February 4, 2019. Presented key research findings to the advisory board.
The Cover It Up team attended the Gathering Partners Conference in May 17-19, 2019 and presented findings from the project to approximately 30 citizen scientists and practitioners.

Status as of January 31, 2020:
MITPPC communications has been strengthening its portfolio of internal communications resources in recognition of the fact that our researchers are our strongest advocates of their work in the community. We support our research teams directly in the following ways:

- Professional media training sessions hosted in conjunction with UMN Relations, to ensure that researchers can comfortably discuss their work with a wider audience
- A digital resource "hub" that includes ready access to MITPPC-branded communications materials, photo assets and other resources
- A simple but comprehensive central contact form.

MITPPC Publications:
Venette, Robert C.; Morey, Amy C. 2019. Chapter 6. Advances in understanding the ecology of invasive crop insect pests and their impact on IPM. In: Kogan, M.; Heinrichs, E.A. (eds) Integrated management of insect pests: current and future developments. Burleigh Dodds Science Publishing, Cambridge, UK. MITPPC is specifically mentioned as an international center of excellence (page 20).

MITPPC Presentations:
Venette, R.C. 2019. A center for research on terrestrial invasive species. Genetic biocontrol of invasive species working group meeting. Minnesota Department of Natural Resources. St. Paul, MN. June 25, 2019.

Venette, R.C.; Koop, H. 2019. Minnesota Invasive Terrestrial Plants and Pests Center (MITPPC): Phase 5. Legislative-Citizen Commission on Minnesota Resources. St. Paul, MN. June 26, 2019.

Venette, R.C. 2019. Cold hardiness of emerald ash borer and its biological control agents. Wisconsin Arborist Association, Green Lake, WI. July 16, 2019. (Delivered 2X to a total of 300+ attendees).

Venette, R.C. 2019. Impact of winter temps on emerald ash borer – what we saw. Minnesota Public Radio. Recorded interview. August 27, 2019.

Venette, R.C. 2019. Pest risk mapping. Guest lecture in Environmental Science, Policy & Management (ESPM) 3015/5015 Invasive Plants and Animals. University of Minnesota, St. Paul, MN. September 19, 2019.

Sub-project #1
Publications:
NaOH extraction paper is under preparation to be submitted in Plant Disease Journal.

Presentations:
North American Invasive Species Management Association (NAISMA). "Rapid and PCR-free DNA Detection of Invasive Species by Nanoaggregation-Enhanced Chemiluminescence", September 30, 2019

Sub-project #2
Publications:
Acebes-Doria, A.L., A.M. Agnello, B.R. Blaauw, G. D. Buntin, D.G. Alston, E.H. Beers, J.C. Bergh, T.E. Cottrell, R. Bessin, S. Chen, K.M. Daane, S. Fleischer, C. Guédot, L.J., Gut, G.C. Hamilton, R. Hilton, K.A. Hoelmer, E.C. Burkness, W.D. Hutchison, et al. 2019. Season-long monitoring of the Brown Marmorated Stink Bug, *Halyomorpha halys* Stål (Hemiptera: Pentatomidae), throughout the United States using commercially available traps and lures. Journal of Economic Entomology, https://doi.org/10.1093/jee/toz240
Published: 10 September 2019

Govidan, B., & W.D. Hutchison. 2019. Influence of temperature on age-stage, two-sex life tables for a Minnesota-acclimated population of the Brown Marmorated Stink Bug, (*Halyomorpha halys*) Insects (submitted, 12/19).

Presentations:
Twine, T., K. Brauman, S. Liess, T. Mayer, R. Noe, B. Keeler, P. Snyder. 2019. Impacts of climate change on water resources and crop yields in Minnesota, USA. Invited oral presentation at the American Geophysical Union Fall Meeting, San Francisco, CA, December 9-13, 2019.

Twine, T., S. Liess, T. Mayer, R. Noe, P. Snyder, K. Brauman, B. Keeler. 2019. Minnesota's rapidly changing climate: Downscaled projections from CMIP5 using WRF. Poster presentation at the American Geophysical Union Fall Meeting, San Francisco, CA, December 9-13, 2019.

Noe, R., Twine, T., S. Liess, T. Mayer, P. Snyder, K. Brauman, B. Keeler. 2019. High resolution climate change projections for Minnesota and impacts on ecosystem services. Oral presentation at the Clean Water Council, St Paul, MN, October 4, 2019.

Keeler, B., S. Liess, T. Mayer, R. Noe, P. Snyder, K. Brauman. 2019. How will climate change affect Minnesota's water resources? Oral presentation at the Minnesota Water Resources Conference, St Paul, MN, October 15, 2019.

Keeler, B., T. Twine, K. Brauman, M. Davenport. 2019. Climate change impacts on Minnesota waters and ecosystem services. Oral presentation to Lutsen Resort, Lutsen, MN, September 18, 2019.

Snyder et al. & Environmental Quality Board. We have been working with state agencies involved in assessing Minnesota's water resources. Results of our downscaled work will be featured in the State of Minnesota's Water report, published by the EQB, in 2020 (in prep.)

Public relations:
Star Tribune: New crop of pests invade—*Warmer, wetter climate attracts invasive insects to Minnesota's orchards and fields.* By, Jennifer Bjorhus Star Tribune OCTOBER 26, 2019.
http://www.startribune.com/a-new-crop-of-invasive-bugs-threatens-minnesota-s-orchards-and-fields/563385312/

Sub-project #4
Publications:
In Review, Restoration Ecology: Revegetation to slow buckthorn reinvasion: Strengths and limits of evaluating management techniques retrospectively. Wragg, Schuster, Roth, Bockenstedt, Frelich, Reich

In Review, Invasive Plant Science and Management: Efficacy and non-target effects of the bud inhibitor herbicide fosamine (Krenite) for control of regenerating European buckthorn. Schuster, Bockenstedt, Wragg, Reich

Accepted, Restoration Ecology: Increased light availability due to forestry mowing promotes regeneration of invasive European buckthorn. Anfang, Schuster, Wragg, Reich

In Review, Forest Ecology and Management: Extended spring and autumn phenology increases biotic resistance of forests to invasion by common buckthorn (*Rhamnus cathartica*). Schuster, Wragg & Reich

Presentations:
Duluth Cooperative Invasive Species Management Area (November 2019). Oral presentation by Wragg to approximately 20 people.
Duluth Invaders R^2ED Team (November 2019). Oral presentation by Wragg to approximately 30 people.

Public relations:
Pioneer Press. https://www.twincities.com/2019/12/02/u-of-m-center-battles-hungry-invasives/

KARE 11. https://www.kare11.com/article/life/home-garden/grow-with-kare/grow-with-kare-be-a-citizen-scientist-and-fight-buckthorn-university-minnesota-native-plants-woods/89-33f5cd4e-a5af-4d26-8e7e-c1655f482f84?utm_source=MITPPC+Master+List&utm_campaign=411ad7fc2d-EMAIL_CAMPAIGN_APRIL_COPY_01&utm_medium=email&utm_term=0_3667ffbf32-411ad7fc2d-189336331

Status as of *July 31, 2020*:
Sub-project 2:
Publications:
*Govidan, B.N., & W.D. Hutchison. 2020. Influence of temperature on age-stage, two-sex life tables for a Minnesota-acclimated population of the Brown Marmorated Stink Bug, (*Halyomorpha halys*). *Insects.* 2020, 11(2), 108; https://doi.org/10.3390/insects11020108 (February).
**paper was well received with >780 full-text views on journal web site within the first 4 months.*

Hanson, A. & W.D. Hutchison. 2020. Degree-day Models and Forecasts for Selected Insect Pest Species in the Midwest Region (BMSB cumulative weekly DDs and 7-day forecasts). https://www.vegedge.umn.edu/mndd – UMN Extension IPM Program, St. Paul, MN (5/01/20).
Govindan, B.N. & W.D. Hutchison. A Logistic Time-temperature Model for Predicting Cold Stress Survival in a Minnesota-Acclimated Population of the Brown Marmorated Stink Bug, *Halyomorpha halys. Entomol. Generalis.* (internal review).

Govindan, B.N. & W.D. Hutchison. Temperature-dependent development, survival and reproduction models of a Minnesota-acclimated population of the Brown Marmorated Stink Bug (*Halyomorpha halys*). *Environ. Entomol*. (In prep.).

Public relations:
Snyder, P., T. Twine, et al. Environmental Quality Board. We have been working with state agencies involved in assessing Minnesota's water resources. Results of our downscaled work will be featured in the State of Minnesota's Water report, published by the EQB, in 2020 (in prep.)

Status as of January 31, 2021:
Sub-project 5:
Presentations:
An oral presentation was given at the 2020 Upper Midwest Invasive Species Conference (Nov. 2020) entitled, "Making better MaxEnt models for invasive species", which presented MITPPC-funded research on species distribution modeling for the European Gypsy Moth.

Poster presentation, 2020 UMISC, entitled "Prioritizing Minnesota's Top Terrestrial Invasive Plants & Pests for Research", which presented information on MITPPC and its prioritization process.

Status as of *July 29, 2021*:
MITPPC presentations
Venette, R.C. 2021. The Minnesota Invasive Terrestrial Plants and Pests Center model. North American Forest Insect Work Conference (on-line). May 28, 2021 (Invited presentation; registration fees paid by USDA Forest Service)

Venette, R.C. & A.C. Morey. 2021. Simplified risk assessments for domestic invasive species. North American Forest Insect Work Conference (on-line). May 27, 2021 (Invited presentation; registration fees paid by USDA Forest Service)

Venette, R.C. 2021. Research on emerald ash borer. Joint hearing of the Minnesota House of Representatives Agriculture and Environment & Natural Resources Finance & Policy committee. On-line hearing. February 5, 2021.

MITPPC staff (Venette, Koop, and Morey) met with Dr. Vanessa Lopez, National Program Manager for Invasive Plants and Biological Control, State and Private Forestry, USDA Forest Service, Washington DC on April 27, 2021 to introduce MITPPC and begin discussions on possible collaborations.

MITPPC Publications
Morey, A.C. & R.C. Venette. 2021. A participatory method for prioritizing invasive species: ranking threats to Minnesota's terrestrial ecosystems. Journal of Environmental Management 290: 112556. https://doi.org/10.1016/j.jenvman.2021.112556

Previously funded sub-projects continue to disseminate findings even though they have ended. A summary of those publications and presentations is presented below by sub-project.

Sub-project 2:
Publications:

Aita, R.C., A.M. Kees, B. H. Aukema, W.D. Hutchison, & R.L. Koch. 2021. Effects of starvation, age, and mating status on flight capacity of laboratory-reared brown marmorated stink bug (Hemiptera: Pentatomidae). Environmental Entomology https://doi.org/10.1093/ee/nvab019 (in press)

Aita, R.C., D.T. Pezzini, E.C. Burkness, C.D. DiFonzo, D.L. Finke, T.E. Hunt, J.J. Knodel, C.H. Krupke, B. McCornack, A.P. Michel, C.R. Philips, A.J. Varenhorst, R.J. Wright, L. Marchi-Werle, W.D. Hutchison, & R.L. Koch. 2021. Presence-absence sampling for herbivorous stink bugs in soybean in the north central region of the United States. Journal of Economic Entomology 114(3): 1362–1372. https://doi.org/10.1093/jee/toab076

Ribeiro, A.V., S.G. Holle, W.D. Hutchison, & R.L. Koch. 2021. Lethal and sublethal effects of conventional and organic insecticides on the parasitoid *Trissolcus japonicus*, a biological control agent for *Halyomorpha halys*. Frontiers in Insect Science (June). https://doi.org/10.3389/finsc.2021.685755

Sub-project 3:
Publications:

Briscoe Runquist, R.D., T.A. Lake, and D.A. Moeller, D.A. 2021. Improving predictions of range expansion for invasive species using joint species distribution models and surrogate co-occurring species. Journal of Biogeography 48: 1693-1705. https://doi.org/10.1111/jbi.14105

Sub-project 4:
Presentations:

Wragg, Peter. February 17, 2021 Cover it Up! https://coveritup.umn.edu/talks

Project status as of *November 23, 2021* (In lieu of report scheduled for *January 31, 2022*):
MITPPC presentations
Venette, R.C. 2021. Pest risk mapping (Guest lecture). Environmental Science, Policy, and Management (ESPM) 3015/5015. University of Minnesota, St. Paul. September 23, 2021.

Venette, R.C. 2021. MITPPC is "the bee's knees" for trees and terrestrial invasive species. Minnesota Society for Arboriculture, St. Paul, MN. October 19, 2021.

Project status as of *June 30, 2022*:
MITPPC presentations
Venette, R.C. 2022. "Research accomplishments in forest entomology from the Minnesota Invasive Terrestrial Plants and Pests Center." North Central Branch Meeting of the Entomological Society of America. Minneapolis, MN. March 22, 2022. (Delivered remotely.)

Venette, R.C. 2022. "Stopping invasive species in our Bloomington backyards – or - Protecting the land from invasive plants, pests and pathogens: putting science into practice." Minnesota Valley Chapter of the Izaak Walton League. Bloomington, MN. June 11, 2022.

University of Minnesota Invasive Species Research Conference, June 28, 2022. Sponsored by the College of Food, Agricultural, and Natural Resources Science (CFANS); University of Minnesota Extension; Minnesota Aquatic Invasive Species Research Center (MAISRC); and the Minnesota Invasive Terrestrial Plants and Pests Center (MITPPC). First ever simulcast presentations via Zoom to Research and Outreach Centers in Ely, Grand Rapids, Cloquet, Crookston, Morris, Lamberton, Waseca, and Rosemount, with follow-up live local demonstrations. Presentations about MITPPC or MITPPC-supported research were delivered by:

- Venette, R.C. "Welcome: what is MITPPC?"
- Becker, R. "What makes a species invasive?"
- Montgomery, R. "How does the data we have play into controlling and mitigating invasives? How do we know what's working?"

Venette, R.C. 2022. "Forward thinking on invasive species research: working at the nexus of climate, conservation, and collections." National meeting of the Association of Education and Research Greenhouse Curators. St. Paul, MN. July 27, 2022.

Publications
Berhardt, C., H. Koop, D. Larkin, C. Lee, A. Morey, M. Schuster, R. Venette, T. Wolf, and P. Wragg. 2022. Managing Invasive Buckthorn. University of Minnesota College of Food, Agricultural, and Natural Resources Science, St. Paul, MN. 14 pages. [Accessed August 11, 2022]

Final Report Summary: MITPPC has delivered information on research updates and accomplishments to diverse audiences around Minnesota. Information is presented through numerous formal presentations and publications. In addition, results of research are being folded into informal communications, including social media and newsletters. This research is affecting discussions about terrestrial invasive species management around the state. In addition, we have seen MITPPC's stature as a national leader in invasive species research steadily grow. As an example, the Upper Midwest Invasive Species Conference is the single largest conference in North America devoted exclusively to the research and management of invasive species. Presentations from MITPPC on terrestrial invasive species far outnumber presentations from any other similar research organization. Results from MITPPC are also being shared with the North American Invasive Species Management Association to reach broader audiences.

VI. PROJECT BUDGET SUMMARY:

A. Preliminary ENRTF Budget Overview:

*This section represents an overview of the preliminary budget at the start of the project. See the attached budget document for an up-to-date project budget, including any changes resulting from amendments.

Budget Category	$ Amount	Explanation
Personnel:	$ 949,619	one research faculty PI: $27,300 (66% salary, 33.8% benefits); 25% FTE for 3 years one research faculty PI: $27,300 (66% salary, 33.8% benefits); 25% FTE for 4 years one graduate research assistant: $22,000 (56% salary 35% tuition 9% benefits); 50% FTE for 3 years one graduate research assistant: $22,000 (56% salary 35% tuition 9% benefits); 50% FTE for 4 years one postdoctoral associate: $45,900 (79% salary, 21.4% benefits); 100% FTE for 3 years one postdoctoral associate: $45,900 (79% salary, 21.4% benefits); 100% FTE for 4 years (More detail to be provided as specific research projects are proposed.)
Professional/Technical/Service Contracts:	$ 12,000	Expert panel member honoraria- approx.4 people x $500 x 2 days (years 1, 2, and 3); engineering services, lab sample analysis. More detail to be provided as specific research projects are proposed (if applicable)
Equipment/Tools/Supplies:	$ 464,000	Consumable lab materials, specimens and other expenses directly related to research (More detail to be provided as specific research projects are proposed)
Capital Expenditures over $5,000:	$ 1	More detail to be provided as specific research projects are proposed (if applicable).
Printing	$ 1	More detail to be provided as specific research projects are proposed (if applicable)
Travel Expenses~~:~~	$34,378	Expert panel travel - approx.12 people x $200 x 2 days (years 1, 2 and 3) Travel directly related to research Travel to advanced technical training outside MN, or travel to professional conferences outside MN to report project results. More detail to be provided for all travel as specific research projects are proposed.
Other:	$ 1	More detail to be provided as specific research projects are proposed (if applicable). Potential examples include fees to publish project results in open access journals.
TOTAL ENRTF BUDGET:	**$ 1,460,000**	

Explanation of Use of Classified Staff: N/A

Explanation of Capital Expenditures Greater Than $5,000: More detail to be provided as specific research projects are proposed (if applicable)

Number of Full-time Equivalents (FTE) Directly Funded with this ENRTF Appropriation: 14

Number of Full-time Equivalents (FTE) Estimated to Be Funded through Contracts with this ENRTF Appropriation: none

Other Funds:

Source of Funds	$ Amount Proposed	$ Amount Spent	Use of Other Funds
Non-state			
State			
General Fund Appropriation MN Legislature 2014: Chapter 312, HF 3172, Article 12, Section 8	$3,400,000	$3,400,000	Funds will be used to support the hire of a Center Director and administrative support for the 8-year project period, and to support additional research projects and will include personnel costs (faculty, graduate students, postdoctoral associates), equipment, materials and supplies necessary for research. Each project is estimated at $100-200K/year for 3-5 years.
M.L. 2015, Ch. 76, Art. 1, Sec. 6a	$5,000,000	$4,792,201.47	Funds will be used to support additional research projects and will include personnel costs (faculty, graduate students, postdoctoral associates), equipment, materials and supplies related directly to research. Each project is estimated at $100-200K/year for 3-5 years.
M.L. 2016, Ch. 186, Sec. 2, Subd. 2a	$3,750,000	$3,125,971.73	Funds will be used to support additional research projects and will include personnel costs (faculty, graduate students, postdoctoral associates), equipment, materials and supplies related directly to research. Each project is estimated at $100-200K/year for 3-5 years.
Institute on the Environment	$2,840	$2840	Funds will be used to convene a panel to discuss the relationship between soybean aphids, an invasive species, soybean production, and the effects of pesticides on the Dakota skipper and other insect populations.
TOTAL OTHER FUNDS:	**$8,400,000**	**$0**	

VII. PROJECT STRATEGY:

A. Project Partners:

Project Partners (not receiving funds):

USDA Forest Service Northern Research Station

Minnesota Department of Agriculture

Minnesota Department of Natural Resources

Minnesota Forest Resource Council

Agencies and organizations involved in invasive species outreach programs so public information is based on the best available science.

Networks of citizen scientists could be an important part of implementing early detection programs and monitoring the effectiveness of control efforts.

This will be updated in more detail once the priorities for research are established.

B. Project Impact and Long-term Strategy:

The Center's ultimate goal is to eliminate, reduce, mitigate or prevent the introduction, expansion or damage done by terrestrial invasive species in Minnesota. Metrics of success include: threat awareness, response efficiency, control effectiveness, non-target species protection, and mitigation strategies. Ancillary goals include: workforce development, citizen engagement, focused research strategies, improved response time to emerging threats, and improved coordination of efforts.

Success will depend on the ability to marshal multi-disciplinary teams in timely and prioritized ways to deliver results. While M.L. 2014 ENRTF and General Fund dollars will be used to conduct a risk assessment and launch initial research or prioritized species, funding is being sought through M.L. 2015 ENRTF to support additional multi-disciplinary research teams. With adequate funding, the Center's efforts are expected to result in numerous, effective prevention and control methods within an eight year time frame for a significant portion of the 15-20 species upon which we will focus.

C. Spending History: N/A

VIII. ACQUISITION/RESTORATION LIST: N/A

IX. VISUAL ELEMENT: see attached

X. ACQUISITION/RESTORATION REQUIREMENTS WORKSHEET: N/A

XI. RESEARCH ADDENDUM:

Peer review will be conducted by internal U of MN process and documentation to be provided to LCCMR

XII. REPORTING REQUIREMENTS:

Periodic work plan status update reports will be submitted no later than January 31 and July 31 each year (every 6 months). A final report and associated products will be submitted between June 30 and August 15, 2022.

Environment and Natural Resources Trust Fund
Minnesota Invasive Terrestrial Pests and Plants Center-- Final Sub Project List
Legal Citation: ML 2014, Ch. 312, Art. 12, Sec. 8
Project Manager: Robert Venette
Project Title: Minnesota Invasive Terrestrial Plants and Pests Center
Organization: University of Minnesota
College/Department/Division: College of Food, Agriculture, and Natural Resource Sciences
Project Budget: $1,460,000
Project Length and Completion Date: 8 years, June 30, 2022
Current Date: August 11, 2022

February 5, 2021

Sub Project #	Sub Project Title	Species	Project Manager	LCCMR Approval Date	Budget	Amount Spent	Balance	Status (select from dropdown menu)
reserve						$0		
	Professional Services (Publication costs and open-access fees for MITPPC research publications)				$6,673	$6,673	$0	
1	Novel diagnostic tools for rapid and	oak wilt	Abdennour	1/12/2016	$271,911	$271,911	$0	Complete
2	Early detection, forecasting, and management of *Halyomorpha halys* (brown marmorated stinkbug)	brown marmorated stinkbug	William Hutchison	1/12/2016	$616,081	$616,081	$0	Complete
3	Climate change and range expanison of	Multiple high-	David Moeller	1/19/2016	$206,335	$206,335	$0	Complete
4	Cover it up!	Glossy and	Peter Reich	12/4/2015	$327,000	$327,000	$0	Complete
5	Terrrestrial invasive species	Multiple high-	Amy Morey	12/09/20	$32,000	$32,000	$0	Complete
					$1,460,000	$1,460,000	$0	
Notes:								

Environment and Natural Resources Trust Fund
Sub-Project Budget of Minnesota Invasive Terrestrial Plants and Pests Center (MITI

Sub-Project Title: MITPPC Sub-Project [1]: Novel Diagnostic Tools for Rapid and Early Detectior
Legal Citation: M.L. 2014, Chp.312, Sec. 8
Sub-Project Manager: Dr. Abdennour Abbas
Organization: University of Minnesota – Minnesota Invasive Terrestrial Plants and Pests Center
Sub-Project Budget: $271,911
Sub-Project Length and Completion Date: *4 years, Dec. 31, 2019*
Project Length and Completion Date: 8 Years, June 30, 2022
Date of Report: December 4, 2020 (final)

ENVIRONMENT AND NATURAL RESOURCES TRUST FUND BUDGET BUDGET ITEM	BUDGET	TOTAL SPENT	TOTAL BALANCE
Personnel (Wages and Benefits) - Total	**$236,938**	**$236,938**	**$0**
One post-doctoral associate, for 3.5 yrs ($48,425), plus the 23% Fringe ($11,138) = $59,563 total per year.			
Graduate Research Assistant: $43,645 ($18,471 annual salary plus $17,665 fringe and $6,394 summer salary with $1,125 fringe) 100% FTE for 1 yr. The student will work under Prof. Juzwick to test the developed assay on real samples, compare performance to the methods and work with the University Plant Disease Clinic for large scale testing.			
Equipment/Tools/Supplies - Total	**$30,452**	**$30,452**	**$0**
Supplies: Chemicals, Reagents, Media and consumables–fungal cells, culture media, nucleic acids,and other related minor equipment	$30,452	$30,452	$0
Travel - Total	**$2,022**	**$2,022**	**$0**
Abbas and Juzwik will receive $1569.50 to present findings and solicit feedback on project development at meetings with academic, public or industrial stakeholders. In each group, $369.50 will be allocated to travels in Minnesota and $1,200 for domestic travel outside of Minnesota.			$0
academic partners and with farmers			
Travel - Domestic: meetings with industrial partners and to seminars to present results of proposed research	$2,022	$2,022	$0
Professional Services	**$2,499**	$2,499	**$0**
Fees for laboratory services, vendor TBD	$2,499	$2,499	$0
COLUMN TOTAL	**$271,911**	**$271,911**	**$0**

Environment and Natural Resources Trust Fund
Sub-Project Budget of Minnesota Invasive Terrestrial Plants and Pests Center (MITPPC)

Sub-Project Title: MITPPC Sub-Project 2: Early Detection, Forecasting & Management of Halyomorpha halys
Legal Citation: M.L. 2014, Chp. 312, Sec. 8
Sub-Project Manager: William D. Hutchison
Organization: University of Minnesota – Minnesota Invasive Terrestrial Plants and Pests Center
Sub-Project Budget: $616,081
Sub-Project Length and Completion Date: May 30, 2020
Project Length and Completion Date: 8 Years, June 30, 2022
Date of Report: December 4, 2020 (final)

ENVIRONMENT AND NATURAL RESOURCES TRUST FUND BUDGET BUDGET ITEM	Budget	TOTAL SPENT	TOTAL BALANCE
Personnel (Wages and Benefits) - Total	**$577,207**	**$577,207**	**$0**
Post-doctoral Assoc. (Soil-Water-Climate UMN): Year 1=$12,240/yr (81.7% salary, 18.3% fringe) 20% time x 1 yr; Years 2-4=$61,200/yr (81.7% salary, 18.3% fringe) full-time x 3 yrs			
Post-doctoral Assoc. (Entomology): $60,225 (81.7% salary, 18.3% fringe) x 4 yrs			
Dr. Robert Koch, Assistant Professor (Partial summer salary, 2 wks): $6,140/yr (74.8% salary, 25.2% fringe) 5.5% during summer months x 4 yrs			
Eric Burkness, Research Fellow: $17,381/yr (74.8% salary, 25.2% fringe) 20% time x 4yrs			
***The initial Underg. Line item (below) was first Re-budgeted to Temp CS, then in '17 to Labor-Represented (all expenses combined, to date)*			
Underg. Student: $12,337/yr (100% salary, 0% fringe) 47 wks/yr x 25 hrs/wk x $10.50/hr x 4 yrs; however, spending for 1 summer UG still charged			
Professional/Technical Services and Contracts - Total	**$5,000**	**$5,000**	**$0**
Dr. Michael Toews, Univ of Georgia (& GA Invasive Spp. Center): $2,500/yr x 4 yrs to	$5,000	$5,000	$0
Minnesota Supercomputing Institute	$0	$0	$0
Equipment/Tools/Supplies - Total	**$16,556**	**$16,556**	**$0**
BMSB Traps, Pheromone Lures for pest detection, @ $2,500/yr x 4yrs.	$13,557	$13,557	$0
Personal Computer (2) for Data entry, mapping ($1500 ea), Year 1	$2,999	$2,999	$0
Travel - Total	**$17,318**	**$17,318**	**$0**
vehicle; monthly lease+mileage): ~$3800/yr x 4yrs.]	$17,318	$17,318	$0
COLUMN TOTAL	**$616,081**	**$616,081**	**$0**

Returned to Reserve

Environment and Natural Resources Trust Fund
Sub-Project Budget of Minnesota Invasive Terrestrial Plants and Pests Center (MITPPC)

Sub-Project Title: MITPPC Sub-Project [3]: Climate Change and Range Expansion of Invasive Plants
Legal Citation: M.L. 2014, Chp. 312, Sec. 8
Sub-Project Manager: *Dr. David Moeller*
Organization: University of Minnesota – Minnesota Invasive Terrestrial Plants and Pests Center
Sub-Project Budget: $206,335
Sub-Project Length and Completion Date: *2 years; June 30, 2019*
Project Length and Completion Date: 8 Years, June 30, 2022
Date of Report: December 4, 2020 (final)

ENVIRONMENT AND NATURAL RESOURCES TRUST FUND BUDGET **BUDGET ITEM**	**Budget**	**TOTAL SPENT**	**TOTAL BALANCE**
Personnel (Wages and Benefits) - Total	**$204,921**	**$204,921**	**$0**
Dr. David Moeller, PI: $22,925 (75% salary, 25% fringe) 8% for 2 yrs			
Dr. Peter Tiffin, PI: $14,539 (75% salary, 25% fringe) 4% for 2 yrs.			
Dr. Ryan Runquist, Post-doc: $113,887 (82% salary, 18% fringe)80% for 2.5 yrs			
2 Undergraduate students: $15,360 (100% salary) for 2 yrs			
Equipment/Tools/Supplies - Total	**$384**	**$384**	**$0**
Supplies- Lab and/or Field: Supplies for field work, such as site characterization (GPS units), flagging, stakes, tape meters	$384	$384	$0
Travel - Total	**$1,030**	**$1,030**	**$0**
pool for 8 weeks per summer for 2 summers ($300/wk car rental+ fuel	$1,030	$1,030	$0
COLUMN TOTAL	**$206,335**	**$206,335**	**$0**

Environment and Natural Resources Trust F
M.L. 2014 Project Budget
Project Title: Cover it up! Using plants to contr
Legal Citation: ML 2014, Ch. 312, Art. 12, Sec
Project Manager: Peter Reich
Organization: University of Minnesota
M.L. 2016 ENRTF Appropriation: $ 327, 000
Project Length and Completion Date: December 31, 2019
Date of Report: December 4, 2020 (final)

ENVIRONMENT AND NATURAL	Budget	Total Spent	Total Balance
BUDGET ITEM (original)			
Personnel (Wages and Benefits)	**$295,816**	**$295,816**	**$0**
2 U of M Post-doctoral Research Associates -			
2 Interns to help with fall field work for 2			
U of M undergraduate students; 1 student to			
Professional/Technical Services and	**$6,000**	**$6,000**	**$0**
Hire a specialist contractor to supply and apply	$6,000	$6,000	$0
Equipment/Tools/Supplies	**$15,432**	**$15,432**	**$0**
Field supplies, tools, seeds, plants,	$15,432	$15,432	**$0**
Travel expenses in Minnesota	**$9,752**	**$9,752**	$0
In-state travel to conference to present project	$452	$452	$0
In-state travel to field sites, including lodging	$9,300	$9,300	$0
COLUMN TOTAL	**$327,000**	**$327,000**	**$0**

Environment and Natural Resources Trust Fund
Minnesota Invasive Terrestrial Plants and Pests Center
M.L. 2015 Sub-Project Budget
Sub-Project Title: MITPPC #5: Terrestrial Invasive Species Prioritization
Legal Citation: M.L. 2014, Chp. 312, Sec. 8
Sub-Project Manager: Amy Morey
Organization: University of Minnesota
Sub-Project Budget: $32,000
Sub-Project Length and Completion Date: December 31, 2020
Date of Report:

ENVIRONMENT AND NATURAL RESOURCES TRUST FUND BUDGET BUDGET ITEM	Budget	AMOUNT SPENT	TOTAL BALANCE
Personnel (Wages and Benefits)	$31,666	$31,666	$0
Postdoctoral Research Associate: $31,666 (79% salary, 21% benefits); 100% for 6 months			
Equipment/tools/supplies			
miscellaneous supplies (bibliographic database software)	$334	$334	$0
COLUMN TOTAL	**$32,000**	**$32,000**	**$0**