SECTION 1. ADMINISTRATIVE INFORMATION

Title: Mapping Climate Change Resistant Vernal Pools in the Northeastern U.S.

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SECTION 2. PUBLIC SUMMARY

Vernal pools of the northeastern United States are important breeding habitat for amphibians. These wetlands typically fill with water from autumn to early spring and dry by summer. Under projections of future climate, some pools may dry earlier than is typical, which in some cases could make it difficult for amphibians to complete metamorphosis successfully. This study evaluated the factors controlling vernal pool inundation (i.e., whether or not a pool has water in it) and generated model predictions of pool-inundation probability under a variety of weather and climate scenarios (e.g., dry, average, and wet weather, and future climate scenarios for the middle and end of the 21st century). Model predictions were used to identify possible hydrologic refugia, defined as pools that could continue to provide wetland habitat and support amphibian breeding under climate change. Using approximately 3,000 inundation observations from 450 pools located on protected areas across the Northeast, from West Virginia to Maine, models were developed linking pool-inundation patterns to various pool characteristics, such as pool-basin size and landcover of the area surrounding pool basins. Models also considered seasonal timing, short-term weather conditions, and long-term climate. Model predictions show the relative likelihood of pools being inundated under various weather and climate scenarios. Pools that show high probability of inundation late in the summer under future climate conditions and under the dry weather scenario could function as potential hydrologic refugia for amphibian breeding under climate change.

SECTION 3. PROJECT SUMMARY

Vernal pools are seasonal wetlands that provide important breeding habitat for a variety of amphibian species. As future climate projections indicate warmer growing seasons and earlier seasonal increases in evapotranspiration, some managers of vernal pools have expressed concern that pools may dry earlier in the season, potentially interfering with completion of amphibian life cycles. In this context, a subset of pools might function as hydrologic refugia by providing wetland habitat later into the year under relatively dry conditions, thus supporting species persistence even as summer conditions become warmer and droughts more frequent. This study used approximately 3,000 field observations of inundation from 450 pools in the northeastern United States—located from West Virginia to Maine—to train machine-learning models for predicting the likelihood of pool inundation. Inputs to these models included pool size, day of the year, climate conditions, short-term weather patterns, and attributes of the landscapes in which pools were embedded. Predictions of pool wetness were generated on a daily time step from late April through late July using three short-term weather scenarios (dry, wet, and average) under historical climate conditions and four sets of downscaled climate projections (2050s and 2080s under Representative Concentration Pathways 4.5 and 8.5). The modeling and inundation prediction process was replicated using four inundation thresholds on wetted area and depth. Model outputs can enable users to examine the inundation thresholds, time points, weather scenarios, and future climate projections most relevant to their management needs. Together with long-term monitoring of individual pools at the site scale, this regional-scale study can support amphibian conservation by helping to identify subsets of pools that may be most likely to function as hydrologic refugia from changing climate conditions.

SECTION 4. REPORT BODY

Purpose and Objectives

Vernal pools of the northeastern United States provide important breeding habitat to amphibians and invertebrates, including several species of conservation concern (Brooks, 2004; Calhoun and others, 2014). These seasonal wetlands typically fill from autumn to early spring and dry by mid-to-late summer (Leibowitz and Brooks, 2007). Climate change in the Northeast may produce earlier and stronger spring and summer evapotranspiration combined with increasing droughts and shifts in precipitation timing (Ahmadalipour and others, 2017; Rodenhouse and others, 2009). As a result, a key management concern for vernal pools under climate change is that some pools might dry earlier in the year than they have historically, potentially interfering with the successful metamorphosis of larval amphibians (Brooks, 2004; Brooks, 2009; Rodenhouse and others, 2009; Walls and others, 2013). In this scenario, a subset of pools that continue to provide late-season wetland habitat might function as climate-change refugia (i.e., hydrologic refugia), supporting species persistence even as evapotranspiration begins earlier, summer conditions become warmer, and droughts become more frequent (McLaughlin and others, 2017; Morelli and others, 2016).

The purpose of this study was to improve understanding of the factors that control inundation patterns in northeastern vernal pools, in order to identify pools that might function as potential hydrologic refugia under climate change. Specific objectives completed over the course of this study included the following:

1. Key drivers of pool-inundation patterns were identified using machine-learning models and field inundation observations from pools located across the northeastern U.S. These drivers included pool attributes (e.g., pool size, geography, and landscape context), seasonal timing of inundation observations, short- and medium-term weather variables, long-term (30-year) climate conditions, and landscape characteristics representing geology, soils, and landcover (e.g., forest biomass and ecosystem type surrounding pools).
2. Pool inundation models were used to generate predicted wetness probability values for all pools in the dataset on a daily time step from late April through late July under various combinations of: (1) weather scenarios representing short- and medium-term precipitation and evapotranspiration; and (2) historical climate conditions as well as climate scenarios for the 2050s and 2080s under the Representative Concentration Pathway (RCP) 4.5 and 8.5 greenhouse-gas scenarios (Knutti and Sedláček, 2013; Randall and others, 2007).
3. Because pool managers identified a need for flexibility in defining pools as providing "inundated habitat," we replicated the pool-inundation modeling procedure using four different inundation metrics defined by varying thresholds of inundation, as described in the "Organization and Approach" section below. These thresholds to define inundation ranged from any amount of standing water (least stringent threshold) to a requirement of at least 15-cm inundated depth and at least 25-m^2 inundated area (most stringent threshold). Use of multiple inundation metrics in modeling allows users of the final products to identify the inundation thresholds most relevant to their needs, depending on species of interest and aspects of reproductive biology (e.g., inundation during timing of egg laying versus during completion of metamorphosis).
4. We evaluated predicted wetness probability values to identify subsets of pools that may be most likely to remain inundated (and thus provide refugia) under future climate scenarios and/or dry weather conditions.

Organization and Approach

We used a dataset of approximately 3,000 field observations of inundation from 450 pools located from West Virginia to Maine, collected between March and July, from 2004 through 2016, as part of the U.S. Geological Survey's Amphibian Research and Monitoring Initiative (ARMI) wetland-breeding amphibians surveys. We calculated four binary inundation metrics to represent presence or absence of inundated wetland habitat according to varying thresholds of inundated depth and area. The H1 metric classified pools as inundated if any amount of water was observed, i.e., inundated depth and area > 0. The H2, H3, and H4 metrics classified pools as inundated if they had inundated depth ≥ 5 cm and area ≥ 5 m^2, depth ≥ 10 cm and area ≥ 15 m^2, and depth ≥ 15 cm and area ≥ 25 m^2, respectively.

The binary inundation metrics were used to train boosted-regression tree (BRT) models that predicted the likelihood of pool inundation based on pool size, day of the year, climate conditions, short-term weather patterns, and soil, geologic, and landcover attributes. Boosted-regression tree models are a machine-learning algorithm used for classification and prediction of complex datasets. Advantages of BRT models include the ability to capture non-linear relationships, handle missing values, and incorporate multiple predictor types, i.e., continuous and categorical variables (De'ath, 2007; Elith and others, 2008; Hastie and others, 2001).

We represented climatic drivers of pool inundation across three time scales. For short-term water inputs, 5-day cumulative antecedent precipitation was calculated as the sum of daily precipitation from the Parameter-elevation Regressions on Independent Slopes Model (PRISM) (Daly and others, 1994). To represent medium-term water-balance conditions, 6-month Standardized Precipitation Evapotranspiration Index (SPEI) data were obtained from the West-wide Drought Tracker (Abatzoglou and others, 2017). SPEI is conceptually similar to the Standardized Precipitation Index (SPI) but also incorporates temperature-related effects on evapotranspiration (Vicente-Serrano and others, 2010). A 6-month timeframe was recently shown to perform well in explaining pool-inundation patterns (Davis and others, 2019). We conducted sensitivity analyses to select the 6-month SPEI timeframe and 5-day precipitation timeframes. To represent long-term climatic drivers of pool inundation, we used 30-year (1981 to 2010) average climate variables from AdaptWest Project (2015).

We constructed preliminary BRT models for the H1 through H4 inundation metrics using a total of 22 predictors describing pool attributes, landscape characteristics, and weather and climate variables. We then conducted a multi-step simplification procedure to arrive at more parsimonious final models by removing predictors that were redundant or that could be removed without adversely affecting model predictive performance (Elith and others, 2008). The final set of simplified models contained 12 predictors: Julian day of inundation observation, 5-day cumulative antecedent precipitation, 6-month SPEI, average April pool inundated area, average April area-to-depth ratio, pool elevation, water-table depth (April-June minimum) and soil hydrologic group (dominant condition) from the Soil Survey Geographic (SSURGO) database (Soil Survey Staff, 2016), landcover type from the National Land Cover Database (NLCD) (Yang and others, 2018) and forest aboveground biomass (North Atlantic Landscape Conservation Cooperative, 2014) in a 50-m radius around pool locations, and Hargreaves reference evaporation and annual heat-moisture index from AdaptWest Project (2015).

We evaluated BRT model performance using three statistics: (1) the percent of deviance in the response variable (inundation metric) explained by the model, (2) the cross-validated correlation coefficient, and (3) the mean area under the curve of the receiver-operator characteristic (ROC-AUC). To compare observed and predicted inundation for model accuracy calculations, a threshold of 0.6 was applied to predicted wetness probabilities to differentiate predictions of "likely dry" from "likely wet" pool-inundation status, because this threshold maximized model prediction accuracy while approximately balancing type 1 and 2 error rates.

We tested model prediction accuracy using leave-one-out cross-validation (LOOCV) by systematically withholding all observations from one pool at a time and generating predictions using all observations from all other pools. This generated a LOOCV accuracy statistic for each pool representing the effectiveness of the modeling approach in predicting that pool's inundation patterns using a model trained on all other pools in the dataset. We then assigned pools to five categories of confidence in model predictions based on combined criteria for LOOCV accuracy and numbers of inundation observations.

We generated predictions of pool wetness on a daily time step from late April through late July using three short-term weather scenarios (dry, wet, and average), under historical climate conditions and four sets of downscaled climate projections (2050s and 2080s under RCP 4.5 and 8.5). This seasonal time period—especially May 15 through July 15—represents a critical period for pool-breeding amphibian life-cycle completion in the Northeast region (Brooks, 2004). Weather conditions were specified as follows: average conditions (SPEI = 0; 5-day cumulative precipitation = 10.8 mm, the median of observed cumulative precipitation values in the modeling dataset), dry conditions (SPEI = -1; cumulative precipitation = 0 mm), and wet conditions (SPEI = 1; cumulative precipitation = 26.0 mm, the 75th percentile of observed cumulative precipitation). The RCP 8.5 scenario generally projects greater change in climate variables than does the RCP 4.5 scenario; detailed descriptions of RCPs and climate projections used in this study are available from AdaptWest Project (2015), Knutti and Sedláček (2013), and Randall and others (2007).

We replicated the modeling and prediction process for four inundation metrics (i.e., thresholds on wetted area and depth). The intent of providing multiple sets of wetness probability predictions was to enable managers and other stakeholders to choose the inundation definitions and time-points of greatest relevance to their efforts. Toward this end, we developed a user-friendly, interactive web application (Cartwright, 2020) that allows users to explore the published datasets from this study by selecting the management unit(s) of interest and the combinations of inundation metric, seasonal time-point, and weather and climate scenarios of relevance to their management contexts. Users can optionally filter results by prediction confidence categories associated with pool-inundation predictions. To make the published dataset and web application more user friendly, only a subset of daily predictions was included for the dates May 15, June 1, June 15, July 1, and July 15. This combination of five discrete time points, three weather scenarios, five climate scenarios, and four inundation metrics yielded a total of 300 predicted wetness probability values for each pool (Cartwright and others, 2020).

In addition to the modeling efforts in this study, the U.S. Geological Survey's ARMI program instrumented 54 vernal pools across 5 management units (National Wildlife Refuges) with a combination of HOBO TidBit V2 (model UTBI-001) and Pendant (model UA-002-08) dataloggers. Sites were selected to represent the range of hydroperiods in the modeling dataset. Loggers were placed in the pool basins at 4 to 5 evenly spaced depths and secured using rebar and zip ties. Data were of insufficient temporal duration to be used for validating hydrologic models in this study but could be useful in subsequent projects on vernal pool inundation and amphibian responses to changing climate conditions.

Project Results, Analysis, and Findings

Climate projections generally indicate warmer and drier summer conditions for vernal pools across management units in this study (figs. 1A and 1B), driven by increased evapotranspiration and longer growing seasons (figs. 1C through 1F). Projected changes were generally greater under the RCP8.5 scenario than the RCP4.5 scenario. Summers are projected to become hotter (fig. 1B) and frost-free period(s) to begin earlier (fig. 1F), suggesting potential for earlier seasonal increases in evapotranspiration if spring conditions become warmer and leaf-out timing shifts earlier. Longer and hotter growing seasons (i.e., increases in growing-degree days, fig. 1E) suggest potential for increased summer drying of some vernal pools.

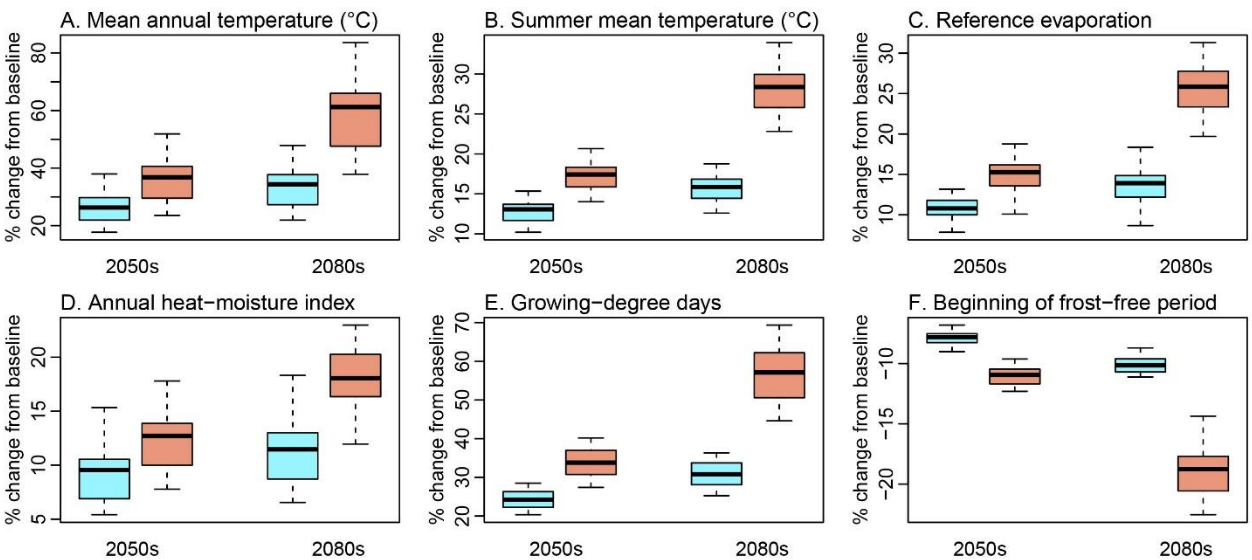

Figure 1. Climate-change projections for the RCP4.5 and 8.5 emissions scenarios (blue and orange, respectively) for the 2050s (2041 through 2070) and 2080s (2071 through 2100), expressed as percent change relative to a baseline historical period (1981 through 2010). Boxplots represent variability across the protected areas ('units') containing vernal pools used in inundation models.

Inundation models showed that pool-inundation patterns were influenced by several key factors (fig. 2, table 1). Partial-dependence plots (fig. 2) show the general response of the H1 through H4 pool-inundation metrics to each predictor variable, holding all other predictors constant, while relative influence values (table 1) indicate the importance of each predictor in explaining the observed pool-inundation patterns (Elith and others, 2008). Holding other predictors constant, predicted wetness probability generally decreased from early May through late July (i.e., from Julian day 120 to 210; fig. 2A), in agreement with known seasonal patterns of pool drying (Brooks, 2004; Brooks, 2009; Leibowitz and Brooks, 2007). Wetness probability increased with increasing 5-day cumulative antecedent precipitation until approximately 40 mm, then leveled off at greater precipitation values (fig. 2B). Across the range of 6-month SPEI values between the 5^{th} and 95^{th} percentiles (dashed vertical lines in fig. 2), inundation likelihood was lowest for SPEI values near -1 (indicating moderate drought) and was greatest for SPEI values between 1 and 2 (indicating wetter-than-average conditions; fig. 2C). Larger pools (i.e., with greater average April inundated area) were more likely to be inundated throughout the season (fig. 2D). Pools with deeper, narrower geometry (i.e., with lower April area/depth ratio) were more likely to be inundated than pools with broad, shallow geometry (fig. 2E), possibly

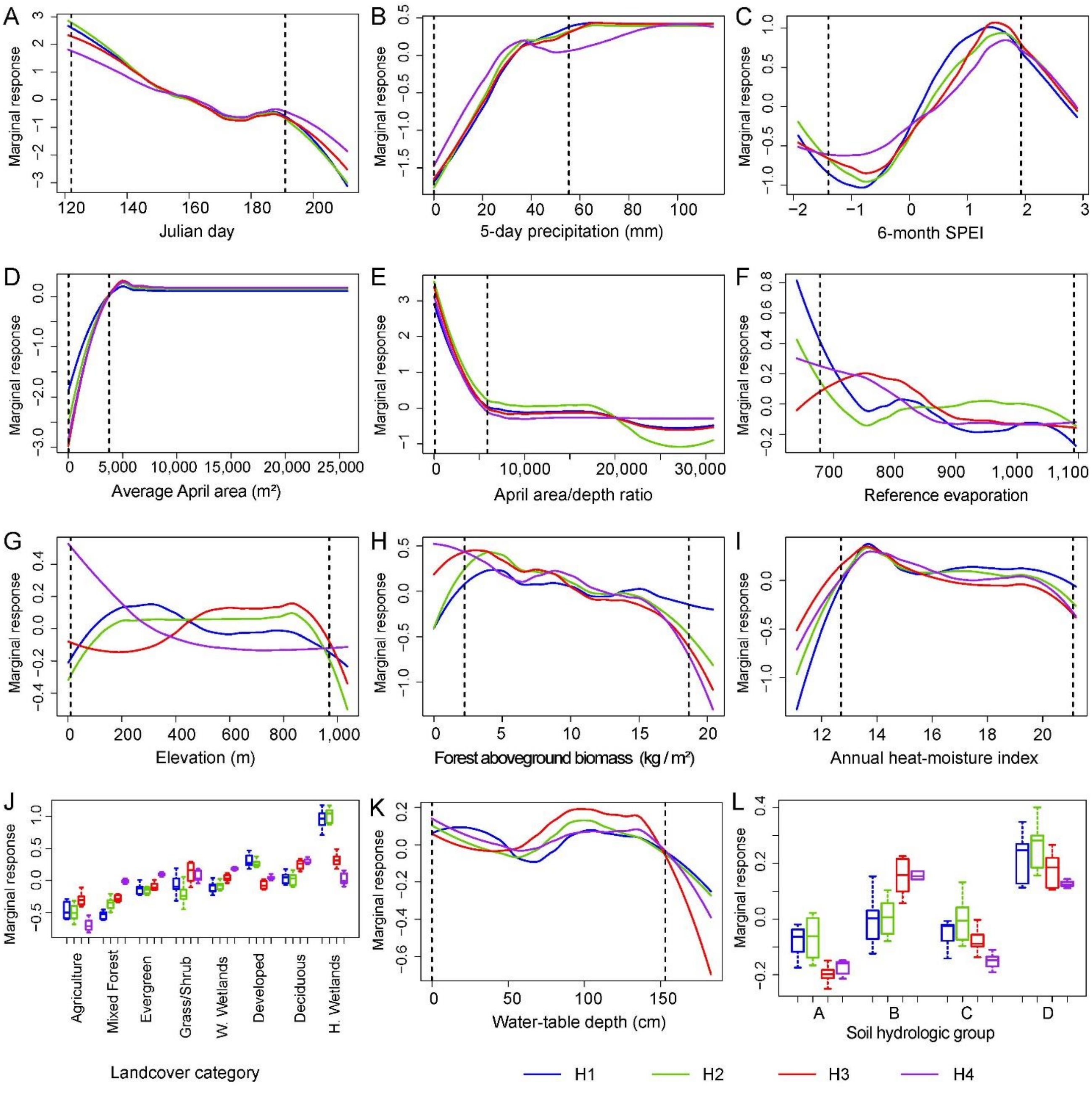

Figure 2. Partial-dependence plots from boosted regression tree models, relating likelihood of vernal pool inundation (vertical axes) with timing, climate, pool, and landscape characteristics. Interpretation of relationships is focused on the region of each plot between the dashed vertical lines, representing 5th and 95th percentiles of the predictors. In (J), W. and H. stand for wooded and herbaceous, respectively.

related to the role of surface evaporation in pool drying. Across the H1 through H4 inundation models, pool size (average April area), Julian day (seasonal timing), 5-day precipitation, and 6-month SPEI were generally the most important predictors of pool-inundation patterns based on relative influence values (table 1). These findings highlight the importance of seasonality, local weather patterns, and pool size and shape in influencing vernal pool hydrology (Brooks, 2004; Brooks and Hayashi, 2002).

Predicted wetness probability generally was lower for pools in warmer and drier climates based on 30-year normal reference evaporation and annual heat-moisture index (figs. 2F and 2I), after accounting for other variables in the models. However, the greater relative influence of 5-day precipitation and SPEI compared to 30-year climate variables (table 1) suggests that shorter-term weather conditions were more important in explaining differences in pool inundation than long-term climate.

Table 1. Model performance statistics and relative influence values for boosted-regression tree models of pool inundation

	H1	**H2**	**H3**	**H4**
Cross-validated correlation	0.72 (0.0063)	0.74 (0.0042)	0.75 (0.0057)	0.75 (0.0032)
Percent deviance explained	0.77 (0.0169)	0.76 (0.0156)	0.75 (0.0184)	0.70 (0.0084)
ROC-AUC	0.93 (0.0032)	0.93 (0)	0.93 (0.0032)	0.93 (0.0042)
	Relative influence values			
	H1	**H2**	**H3**	**H4**
Average April area	13.57 (0.26)	**17.47 (0.36)**	**23.57 (0.48)**	**29.61 (0.46)**
Julian day	**16.67 (0.24)**	17.0 (0.31)	13.37 (0.23)	11.03 (0.26)
5-day precipitation	12.42 (0.19)	11.36 (0.2)	10.03 (0.23)	8.29 (0.15)
6-month SPEI	11.38 (0.21)	10.29 (0.21)	9.8 (0.16)	7.89 (0.17)
April area/depth ratio	9.1 (0.15)	8.48 (0.16)	8.64 (0.11)	9.16 (0.25)
Reference evaporation	9.22 (0.21)	7.62 (0.21)	8.37 (0.26)	8.35 (0.23)
Forest aboveground biomass	6.6 (0.19)	6.71 (0.17)	6.85 (0.12)	5.78 (0.15)
Annual heat-moisture index	6.19 (0.3)	5.68 (0.22)	5.63 (0.18)	5.06 (0.17)
Elevation	5.16 (0.12)	5.28 (0.19)	4.52 (0.1)	5.74 (0.18)
Landcover category	4.36 (0.17)	4.75 (0.17)	4.36 (0.15)	4.3 (0.14)
Water-table depth	3.46 (0.09)	3.25 (0.13)	3.09 (0.11)	2.87 (0.11)
Soil hydrologic group	1.86 (0.11)	2.1 (0.13)	1.78 (0.09)	1.95 (0.08)

Notes: Values are presented as means (standard deviations in parentheses) across 10 iterations for each model. For each inundation metric (H1 through H4), the predictor with greatest mean relative influence is bolded.

Several landscape characteristics also helped explain pool-inundation patterns, although landscape characteristics were generally less influential than pool size, weather, or seasonal timing (table 1). Pool inundation did not show clear, unambiguous relationships to elevation (fig. 2G) and elevation had generally low relative influence across models (table 1), suggesting that elevation was not a strong driver of pool inundation after accounting for weather and climate conditions. Predicted wetness probability showed moderate declines with increasing forest aboveground biomass in a 50-m radius around pools (fig. 2H). Wetness probability was generally lowest for pools in predominantly agricultural areas and highest for pools surrounded by herbaceous wetlands (fig. 2J). Little difference in inundation likelihood was apparent between pools surrounded by deciduous versus evergreen forest. The influence of water-table depth (minimum from April to June) was low across models (table 1) and did not show clear relationships to pool inundation (fig. 2K). Although relative influence of soil hydrologic group was also low, pools located on well-drained soils (group A) had lowest predicted wetness probability whereas pools on poorly drained soils (group D) had highest predicted wetness probability (fig. 2L), suggesting that vernal pool inundation may have been supported by soil types with high runoff potential and poor drainage.

Pools demonstrated a variety of modeled seasonal dry-down patterns in response to short-term weather and future climate scenarios (fig. 3). Pools were generally predicted to become dry earlier under the dry weather scenario and later under the wet weather scenario, although responses of modeled pool drying to weather and climate scenarios varied substantially across pools. For example, under historical climate conditions the pool in fig. 3A was predicted to dry in late May in dry weather, early July in average weather, and in late July in wet weather. Using projected climate conditions for the 2080s under RCP 8.5, this pool was projected to become dry slightly earlier under dry conditions and roughly 2 weeks earlier under average conditions, with no change in inferred drying day under wet conditions. Some pools, especially in the dry weather scenario, were predicted to be dry during the entire seasonal modeling period. For example, under both historical and future climate scenarios, the pool in fig. 3B was predicted to be dry (wetness probability < 0.6) from May 1 through July 15 under the dry and average weather scenarios and was predicted to dry in late May under the wet weather scenario. By contrast, other pools (example in fig. 3C) were predicted to be inundated (wetness probability > 0.6) during the entire seasonal modeling period. Under both historical and future climate conditions, this pool was projected to remain inundated past July 15 under all weather scenarios

Maps of predicted wetness probability—stratified by inundation metric, seasonal time point, and weather and climate scenarios—can be used to identify pools with the greatest likelihood of remaining inundated under a variety of conditions. Examples for the Patuxent Research Refuge in Maryland (fig. 4) show subsets of pools with predicted wetness probability >0.6 (in blue) under the dry weather scenario for two seasonal time points and two climate scenarios. Such maps can highlight subsets of pools that are projected to remain inundated under adverse weather conditions (i.e., the dry weather scenario), late-season time-points (e.g., July 1 or July 15), and/or future climate projections. Moreover, modeled pool drying curves (fig. 3), can be combined with maps of predicted pool wetness probability (examples in fig. 4) to identify potential vernal pool refugia according to inundation thresholds and dates of interest. Pools that show relatively high late-season predicted wetness probability even under dry weather and future climate scenarios may be of particular interest as potential hydrologic refugia and may warrant long-term observational studies.

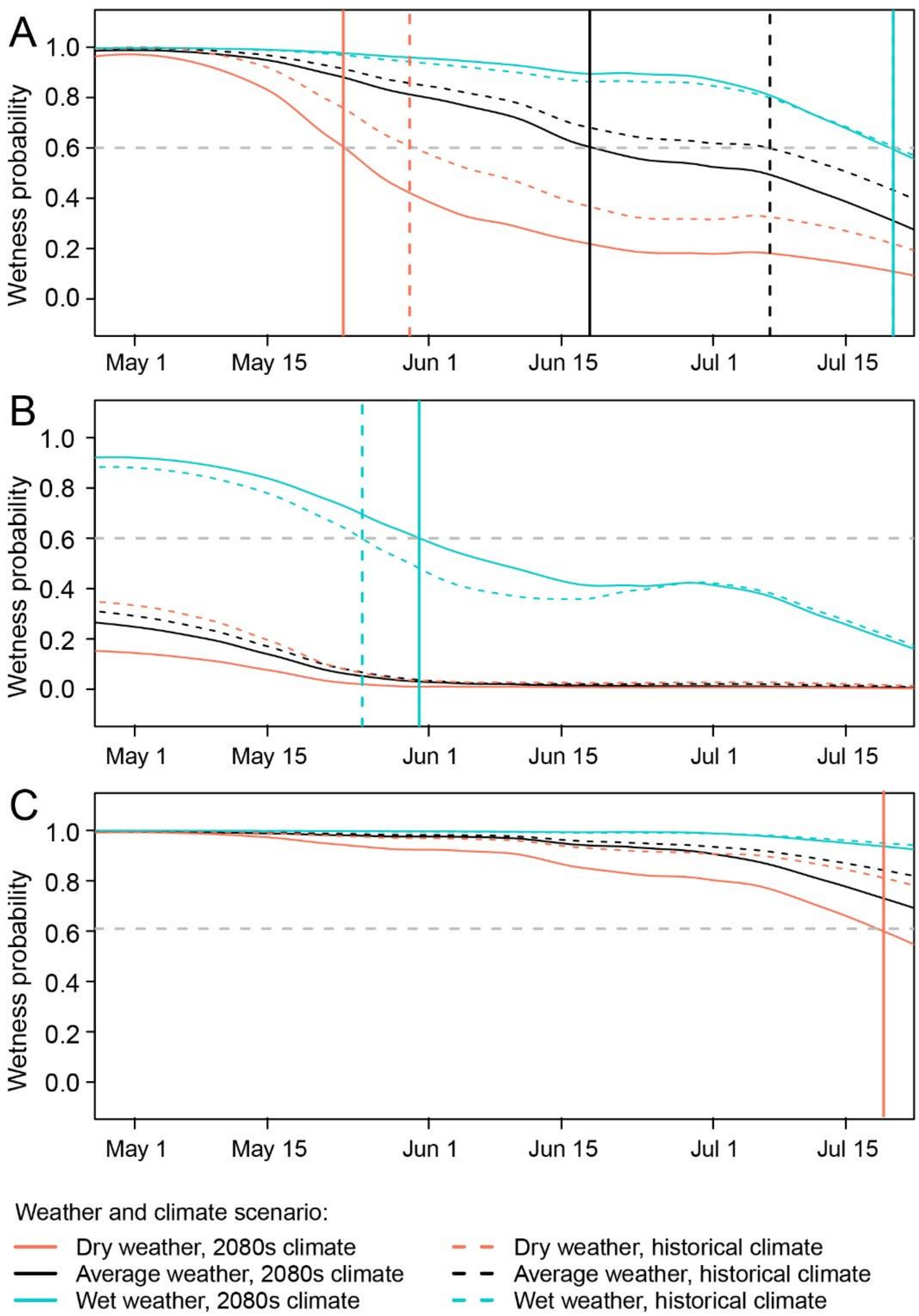

Figure 3. Examples of modeled wetness predictions for three pools with differing responses to weather, climate, and seasonality. Curves depict model predictions of wetness probability for the dry, average, and wet weather scenarios (in orange, black, and blue, respectively) using the H2 inundation definition, from models with historical climate (dashed lines) and projected climate in the 2080s under RCP 8.5 (solid lines). Pools were predicted to be “likely dry” once their wetness probabilities fell below 0.6, corresponding to inferred drying days depicted as vertical lines. Symbology for inferred drying days (colors and dashed-versus-solid vertical lines) matches symbology for seasonal curves. These example pools had cross-validation accuracy of (A) 93%, (B) 96%, and (C) 100%.

To facilitate these explorations of model predictions from this study along with identification of potential refugia under a variety of possible refugia definitions, published model predictions from this study (Cartwright and others, 2020) are available through a user-friendly, interactive web application (Cartwright, 2020; fig. 5; see "Scientific Products" section below).

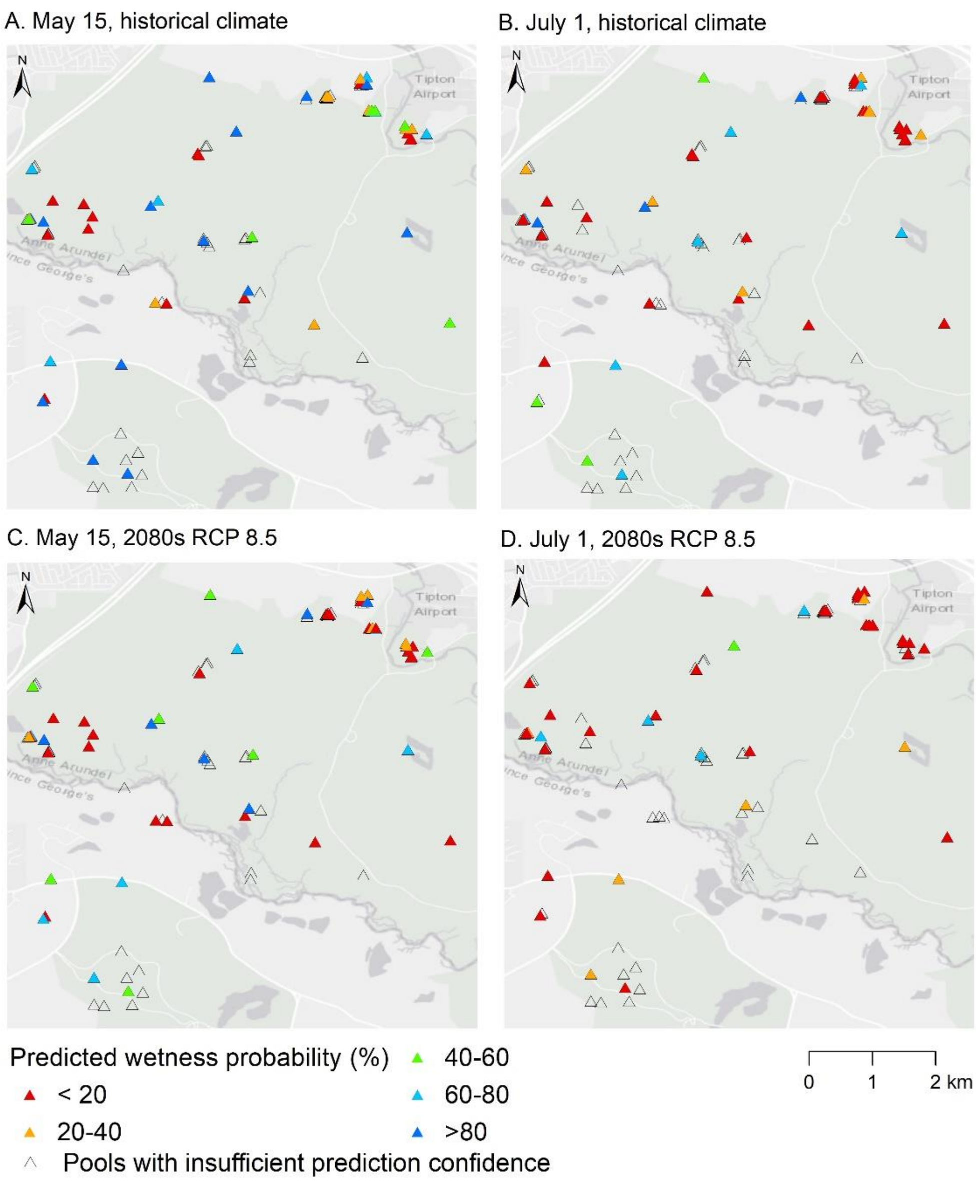

Figure 4. Maps of predicted wetness probability for vernal pools at the Patuxent Research Refuge in Maryland, depicting likelihood of inundation on (A and C) May 15 and (B and D) July 1, using (A and B) historical climate variables and (C and D) projected climate variables for the 2080s under RCP 8.5. All predictions are for the H1 inundation metric and the dry weather scenario. These are four examples of 300 sets of wetness probability predictions generated under various inundation definitions, seasonal time points, and weather and climate scenarios. Predictions are displayed only for pools categorized as having "moderately high" or "very high" prediction confidence based on cross-validation accuracy and numbers of observations; all other pools are displayed as hollow triangles. Base map courtesy of Esri; sources: Esri, DeLorme, HERE, MapmyIndia.

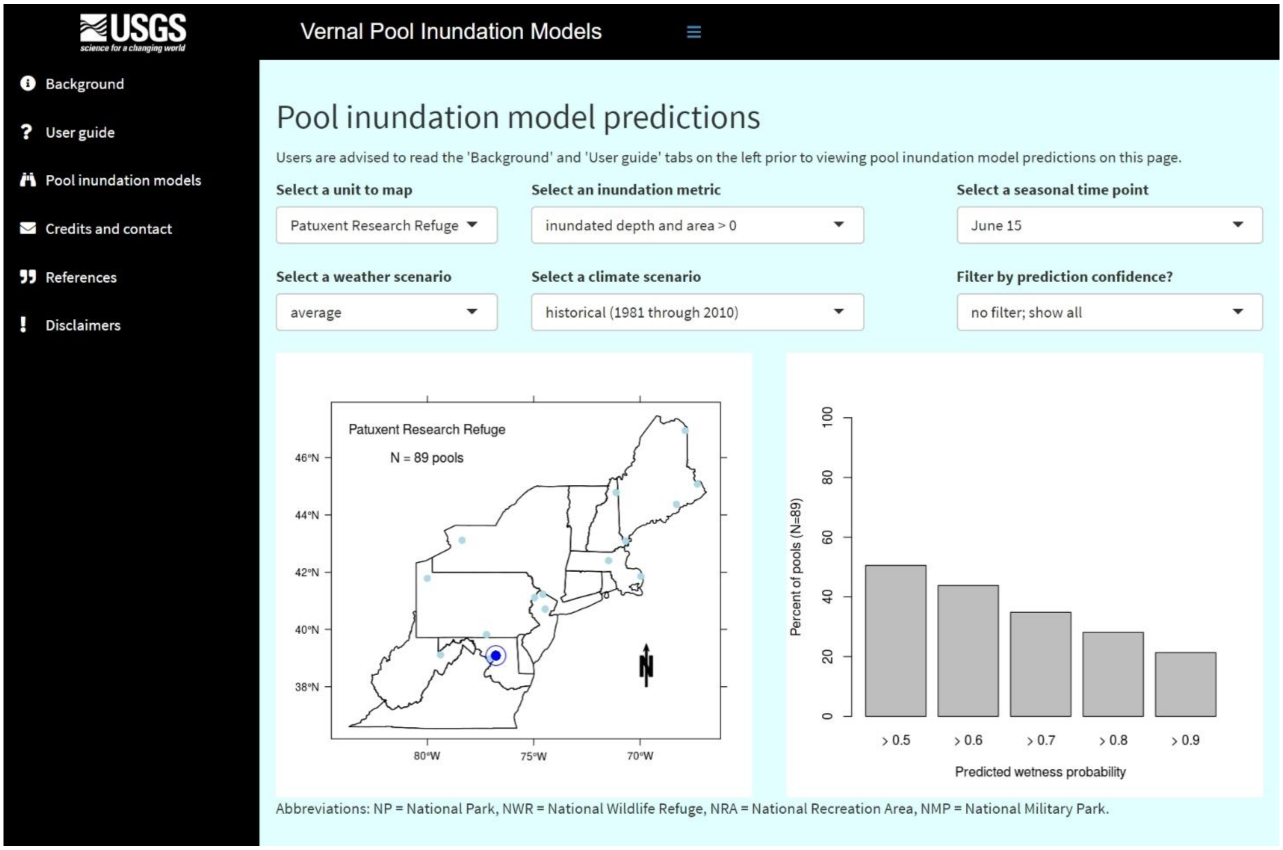

Figure 5. Screen shot of the web application (Cartwright, 2020), which allows users to explore the model outputs from the study in an interactive format.

Conclusions and Management Applications

Findings from this study underscore existing management concerns that climate change may cause some vernal pools to dry earlier in the season than they have historically. Projected changes in pool drying dates are ecologically important because of the potential to interfere with completion of amphibian life cycles. However, modeling results from this study suggest variability among pools in their hydrologic responses to weather and climate scenarios. This variability implies that some pools are more likely than others to remain inundated later in the season under dry weather conditions and future climate projections. Such pools are candidates as potential hydrologic refugia. However, we caution that these modeling results cannot be used to conclude definitively that any particular pool will necessarily provide a future hydrologic refugium. Rather, we suggest that modeling results may be most useful to vernal-pool managers by highlighting pools (e.g., potential refugia) that may warrant more in-depth analysis and long-term hydrologic monitoring. For such pools, inundation observations and amphibian monitoring data may be especially useful if obtained across multiple years with varying weather conditions and especially during abnormally warm or dry seasons (i.e., droughts). Pools that were identified in our models as having potential to provide hydrologic refugia and which are independently observed to remain inundated and act as sites of successful amphibian reproduction based on future studies may be of special interest to managers working to conserve amphibian populations under climate change.

Outreach and products

1. Scientific products

Cartwright, J., Morelli, T., and Grant, E., 2020, Inundation observations and inundation model predictions for vernal pools of the northeastern United States: U.S. Geological Survey data release, https://doi.org/10.5066/P9CP2NUD.

Cartwright, J., 2020, Vernal Pool Inundation Models web application, https://www.usgs.gov/centers/lmg-water/science/vernal-pool-inundation-models?qt-science_center_objects=0#qt-science_center_objects.

2. Presentations and workshops

Morelli, T., Cartwright, J., and Grant, E., 2018, Vernal pool threats: How might climate change alter vernal pool management considerations? Presented at Of Pools and People: Translating Vernal Pool Research into Desired Management Outcomes, Ashland, MA, October 25, 2018.

Cartwright, J., 2019, Mapping climate change refugia for vernal pools. Webinar presentation for the Northeast Climate Adaptation Science Center (NE CASC), May 1, 2019.

Cartwright, J., 2020, Seasonal Wetland Refugia: Identifying Hydrologic Resistance to Warming and Drought in Vernal Pools and Playas. Seminar to be presented remotely at the North American Congress for Conservation Biology, Denver, CO, July 29, 2020.

3. Communications

This project benefited from communication with the "Of Pools and People" working group (www.vernalpools.me) and natural-resource managers in New Hampshire (Department of Environmental Services, Water Division) and Maine (Natural Areas Program). We received feedback from a May 2019 webinar hosted by NE CASC that helped shape several aspects of the project trajectory, including (1) use of multiple inundation metrics, (2) use of several seasonal time points, and (3) the usefulness of presenting modeling outputs in a user-friendly interactive format, through the web application (Cartwright, 2020).

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