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CORRELATES OF VERNAL POOL OCCURRENCE IN THE MASSACHUSETTS, USA LANDSCAPE

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Abstract: Vernal pool wetlands are at risk of destruction across the northeast United States, due in part to their diminutive size and short hydroperiods. These characteristics make it difficult to locate vernal pool habitats in the landscape during much of the year, and no efficient method exists for predicting their occurrence. A logistic regression procedure was used to identify large-scale variables that influence the presence of a potential vernal pool, including surficial geology, land use and land cover, soil classification, topography, precipitation, and surficial hydrologic features. The model was validated with locations of field-verified vernal pools. The model demonstrated that the probability of potential vernal pool occurrence is positively related to slope, negatively related to till/bedrock surficial geology, and negatively related to the proportion of cropland, urban/commercial, and high density residential development in the landscape. The relationship between vernal pool occurrence and large-scale variables suggests that these habitats do not occur at random in the landscape, and thus, protection *in situ* should be considered.

Key Words: land use, landform, predictive model, surficial geology, topography, vernal pool

INTRODUCTION

Vernal pools are a unique class of isolated, ephemeral wetlands, characterized by cyclical periods of inundation and drying. These habitats increase the biodiversity potential of a landscape by providing habitat for rare or uncommon species (Collinson et al. 1995, Semlitsch and Bodie 1998). A range of wetland sizes and hydroperiods in a landscape influences species diversity (Collinson et al. 1995, Higgins and Merritt 1999, Babbitt and Tanner 2000, Snodgrass et al. 2000). In particular, some species have adapted to the annual drying of these habitats (Wilbur 1980, Wiggins et al. 1980, Higgins and Merritt 1999, Schwartz and Jenkins 2000) and are largely excluded from more permanent breeding habitats (Collinson et al. 1995, Pechmann et al. 2001). Populations of wetland-dependant organisms may be limited by the presence of suitable breeding habitat in the landscape (Berven 1995), and metapopulation grouping is structured by the spatial availability of vernal pools, which serve as dispersal intermediaries (Gibbs 1993, Griffiths 1997, Semlitsch and Bodie 1998).

Vernal pools are clustered in the landscape (Brooks et al. 1998), yet the underlying causes for this distributional pattern are poorly understood. The combination of land use and topographic and geologic characteristics in an anthropogenically altered landscape influences the presence of these habitats (Williams 1987), and local hydrologic flowpaths influence their formation, linking these surficially isolated basins with the surrounding landscape (Cook 2001). Wetland formation and abundance can also be related to the hydrogeologic setting (Godwin et al. 2002) and the glacial geology of a given landscape (Palik et al. 2003), although the distribution of isolated depressional wetlands in relation to local geologic features can vary geographically (Tiner 2003).

Protection of vernal pools and other small, isolated wetlands suffers, at least in part, from a lack of efficient methods for locating these habitats in the landscape. Current methods typically rely on aerial photograph interpretation combined with field-verification of potential habitats (Brooks et al. 1998, Burne 2001, Calhoun et al. 2003), which can be costly and inefficient. Future improvements in locating fine-scale landscape features include LIDAR (LIght Detection And Ranging; O'Hara 2002) or other remote-sensing technology (Townsend 2001). Until this new technology becomes widely available, I have developed a tool to locate vernal pool wetlands using readily-available geo-spatial datalayers. This approach will benefit the assessment of a landscape for its biodiversity potential and the potential to maintain amphibian metapopulations.

In this paper, I examine the relationship between landscape-scale variables and vernal pool occurrence

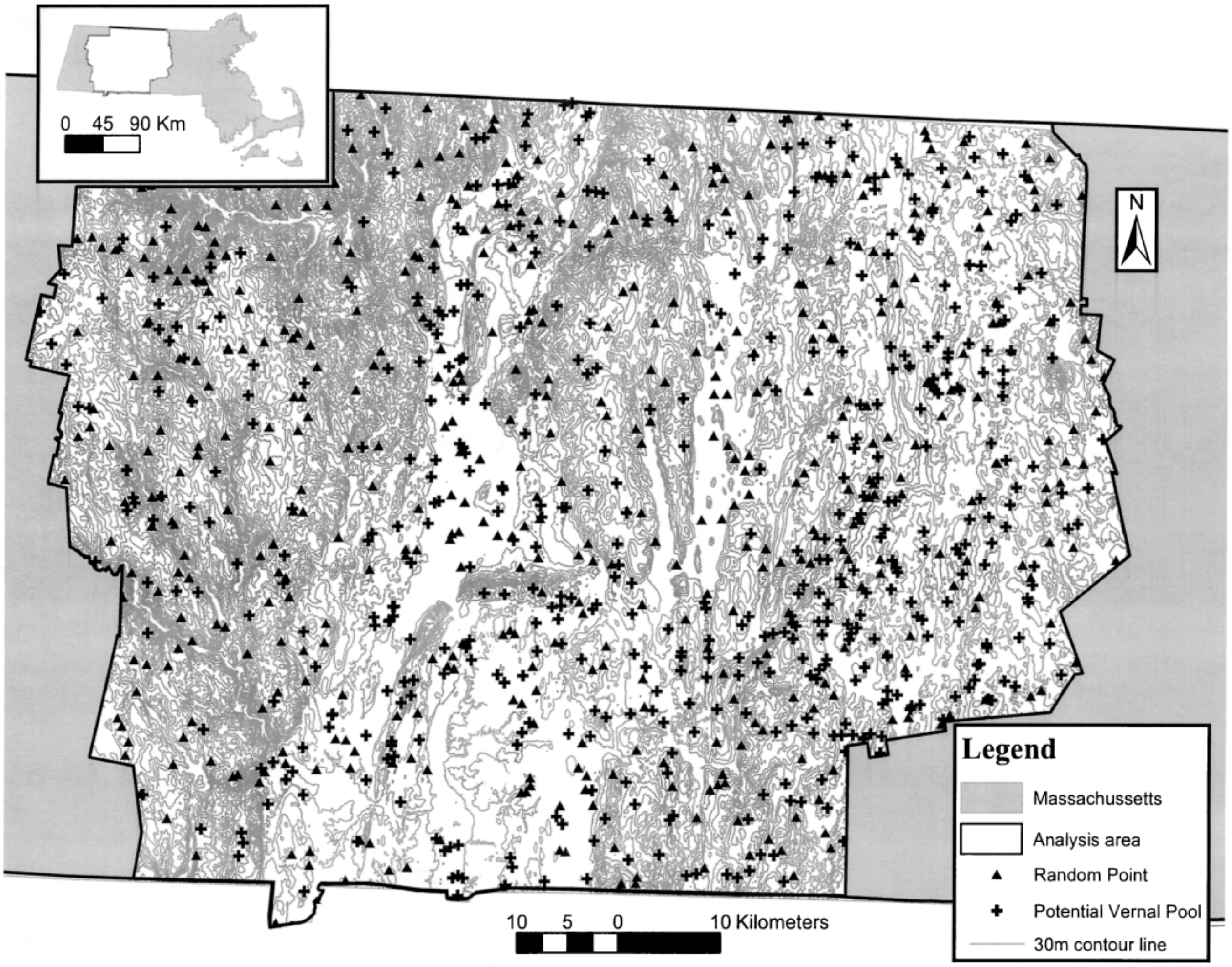

Figure 1. Location of the study area in Massachusetts, USA (inset), including locations of the 500 potential vernal pool and 500 random sample points, with a plot of the topographic relief in the study area. Potential vernal pools, as mapped by the natural heritage program (MassGIS 2002), are not equivalent to certified vernal pools, which are protected under Massachusetts law (Kenney 1995).

in central and western Massachusetts, USA and test the ability to predict the location of a vernal pool using these variables.

METHODS

Data Acquisition

Most data layers were obtained from the Massachusetts GIS website (MassGIS 2002), including surficial geology (1:250 000), land use (1:25 000), 3-m contour line data (interpolated points from 1:5 000 DLG), and hydrography (perennial streams, 1:25 000). Mean annual precipitation data (PRISM) were obtained from the Oregon Climate Service (OCS 1998; 1:250 000). Soils data were obtained from the USGS for the conterminous United States, derived from the state soil geographic (STATSGO) data base (NRCS 1998; 1:250 000 soil survey).

The study area encompassed a 7,224 km^2 area of central and western Massachusetts, including the Connecticut River Valley and portions of the Berkshire Mountains (Figure 1). I chose this analysis area because it was the only region where combined coverage of (1) surficial geology, (2) soil, (3) land use, (4) topography, (5) hydrology, and (6) PRISM annual average precipitation datalayers was available.

Potential vernal pool (PVP) points ($n = 500$) were sampled from a universe of 6603 potential vernal pool locations located in the study area (Fig. 1). A potential vernal pool has not been field-verified, and no documentation of breeding by obligate amphibian or invertebrate taxa has been collected. Potential vernal pools were digitized from aerial photograph interpretation by the Massachusetts Natural Heritage Program (Burne 2001). Because of limitations inherent to interpretation of aerial photography, the digitized locations of PVPs do not include small pools (e.g., those less than 38 m in diameter) and those located under heavy conifer canopies (Brooks et al. 1998, Burne 2001). Points ($n = 500$) were randomly generated using the Animal Movement Analyst Extension (RP; Hooge and Eichenlaub 2000). Random points represent the remainder of the landscape and are used to contrast landscape characteristics with those associated with potential vernal pools in a logistic regression model, where a potential vernal pool is coded as ‘‘1’’ and a random point is coded as ‘‘0’’, indicating absence of a potential vernal pool. All data were combined in a GIS (ArcView v. 3.2, ESRI, Redlands, CA) to develop the model datasets. Statistical analyses and model development were conducted in SAS (V8, SAS Institute, Cary, NC). Each of the 1000 sampling points was assigned characteristics based on landscape position. Points missing data were not included in model development (11 of 500 PVP, 16 of 500 RP). A total of 973 points had sufficient data to run the logistic regression model selection procedure.

Data Processing

I included two hydrology-associated variables to develop the model: (1) distance to a stream and (2) average annual precipitation. I hypothesized that potential vernal pools would have a greater association with perennial stream surficial hydrologic features and that the relationship would not hold for random points in the landscape. The distance from each point to the nearest perennial stream was calculated and included in model development (MINDIST). The PRISM mean annual precipitation variable was also included in model development because areas with greater precipitation may be more likely to form a vernal pool (Brooks 2004).

Surficial geology (GEO) was entered in the logistic regression model development as a categorical variable with four categories (fine grained, floodplain/alluvium, sand/gravel, and till/bedrock). Till/bedrock had the greatest frequency in the landscape (67% of random and potential points were associated with this surficial geology type) and was used as the reference category in model development.

Land use was reclassified from 21 to 7 categories: cropland (CROP), pasture/open land (OPEN), forest (FOR), wetland/water(WATER), high density residential (HIGHD; multi-family and < 0.2 ha lots), low density residential (LOWD; > 0.2 ha lots), and urban/commercial (URBCOM). Wetland/water land use was excluded from the analyses so the association between anthropogenic land use conversion and the presence of a PVP could be tested.

In order to describe the relationship between the proportion of land-use types and the presence of a vernal pool, the percent of cropland, pasture/open land, high density residential development, low density residential development, and urban/commercial development was summarized within 50 m of each PVP or RP. The conservative distance of 50 m was based on hydrologic research by Phillips and Shedlock (1993), who determined that ground water from wells located 45 m from a temporary pool was more similar to surface water sampled from the pool, while water sampled from wells 60 m away was less similar to the surface water.

Because I hypothesized that vernal pools would be more likely to be found on flatter terrain and less likely to be found on dry, southern-facing slopes, I included slope and aspect variables in the model development. I developed 6-, 10-, and 30-m triangulated irregular network (TIN) data layers from the 3-m contour line data to identify the spatial scale of topographic information that could best explain the presence of vernal pools. Because scale of topographic data available to land managers can vary across a landscape, I wanted to determine the utility of this approach for individuals who may not have access to fine-scale data. I used the slope and aspect information from the TIN layers to develop the logistic regression models.

Model Development

I used univariate analyses to test for differences between random and potential vernal pool points in order to identify variables to exclude from model development. I evaluated the continuous variables (CROP, OPEN, URBCOM, HIGHD, LOWD, SLOPE, ASPECT, and MINDIST) for independence using a Mann-Whitney U test, and I included variables in the second stage of model development that were significantly different ($\alpha < 0.10$) between random and vernal pool points. I used a Chi-square test to determine the independence of categorical variables (GEO, PRISM, and STATSGO soil great group [SOIL]) and included those that differed between random and potential vernal pool points ($\alpha < 0.10$). Based on the results of these univariate tests, the variables PRISM and LOWD were excluded from the second stage of model development, and all other variables were used to develop the final logistic regression models.

I used forward stepwise logistic regression to model the probability of locating a vernal pool in relation to the independent variables, including interactions between slope or surficial geology with all land-use var-

Table 1. Parameters, signs of the coefficients, parameter estimates (β), standard errors, and the odds ratios for each parameter ($e^{(\beta i)}$) in the final logistic regression model. All variables included in the model were significant to at least the $P < 0.01$ level.

Parameter	Class	Relationship	β	SE	$e^{(\beta i)}$
Intercept			0.38	0.11	1.46
SLOPE (10m)		−	−0.12	0.02	0.89
GEO	Sand/gravel	+	0.76	0.18	2.14
	Fine grained	+	1.53	0.56	4.62
	Floodplain/alluvium	+	0.87	0.29	2.38
CROP		−	−2.57	0.49	0.08
URBCOM		−	−1.90	0.50	0.15
HIGHD		−	−2.89	0.62	0.06

iables. I used a conservative criterion for the variables to enter and remain in the model ($p < 0.15$; Hosmer and Lemeshow 2000).

Model Validation

I evaluated the predictive performance of the final logistic regression model using two independent datasets. First, I developed a validation data set, using a new subset of 500 PVP and 500 random points. Second, I tested the performance of the model using data on 706 certified vernal pools (CVP; MassGIS 2003) located in the study region. Certified vernal pools have been mapped and are potentially afforded protection under Massachusetts's laws and regulations (Kenney 1995, Burne 2001).

RESULTS

Evaluation of initial models indicated that the slope variable was important in a logistic regression model predicting the presence of a potential vernal pool. Using 25% of the PVP points (1,626 points) and the TIN developed at 6-m resolution, I determined that 95% of potential vernal pool points were located on slopes between 0 and 9.3 (mean = 3.17, SD = 3.27, max = 28.8°).

The median distance to the nearest perennial stream was significantly different between random points and potential vernal pools (K-W H= 6.19, df = 1, p = 0.013). However, the variable MINDIST was not chosen in the final logistic model predicting the occurrence of a vernal pool (Table 1).

Model Selection

Based on the fit statistics (AIC, Hosmer-Lemeshow statistic, r^2, percent concordant, and the false positives and negatives), I found the best model to predict potential vernal pool occurrence included slope (derived from the 10m TIN surface), surficial geology type (GEO), and the percent of cropland (CROP), urban/commercial development (URBCOM), and residential development on less than 0.2 ha lots (HIGHD). I used this model (Table 1) to determine the predictive performance of the logistic regression model and to interpret the potential for landscape persistence of these habitats.

Including slope information from the more detailed 6m TIN surface did not result in a increase in model fit, while slope information from the less detailed 30 m TIN resulted in a decreased fit (Table 2).

Holding slope constant at zero and assuming till/bedrock surficial geology type, I investigated the relationship between the land-use variables in the model and the occurrence of a potential vernal pool (Figure 2). I found that a probability level of $\alpha = 0.53$ maximized the sensitivity and specificity and used this

Table 2. Fit statistics (Hosmer-Lemeshow statistic, AIC, R^2, percent concordant, false positive and negative observations) for models including slope information at 6-, 10- and 30-m resolution used to derive the slope and aspect data for model development. All models were developed using a forward-stepwise procedure as described in text. The three models differed only in the scale of the slope variable and included the variables slope, percent of cropland within 50 m of a point (CROP), percent of high density residential development within 50 m of a point (HIGHD), percent of urban and commercial development within 50 m of a point (URBCOM), and surficial geology (GEO). The model including slope information at 6m resolution did not adequately fit the data (Hosmer-Lemeshow $P < 0.01$).

Model	SLOPE scale	HL	df	p	AIC	R^2	% concordant	false +	false −
1	6m	20.08	8	0.01	1202.4	0.15	73.3	31.0	33.1
2	10m	10.44	7	0.17	1219.6	0.14	68.9	35.0	35.5
3	30m	3.97	7	0.78	1234.4	0.13	66.1	36.2	34.6

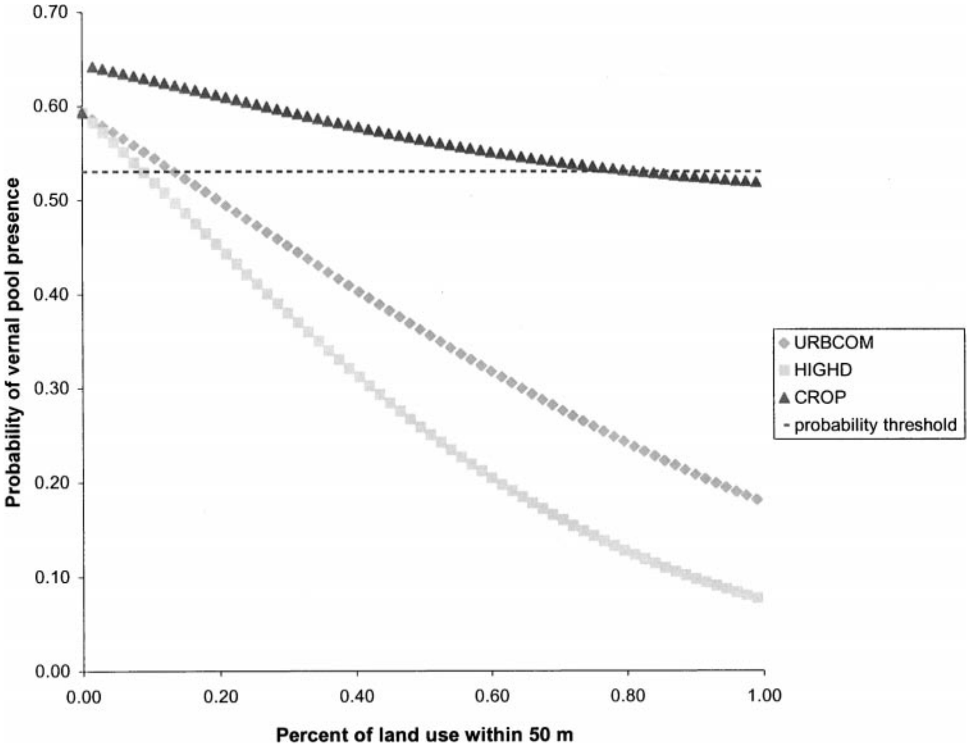

Figure 2. Plot of the predicted probability of vernal pool presence using the logistic model including SLOPE, GEO (surficial geology), and the percent of cropland (CROP), urban/commercial development (URBCOM), and residential development on less than 0.2 ha lots (HIGHD) within 50 m of a point. We calculated the probability of PVP presence by setting GEO to the reference category (till/bedrock) and assuming 0° slope. The probability for each land-use type was fit independently, and we assumed that the remainder of the buffer surrounding each point was occupied by forest cover, with no interaction between land-use types. The probability threshold is located at $\alpha = 0.53$, where a value above 0.53 is considered a predicted event.

probability level as the cutpoint to indicate a predicted event (Hosmer and Lemeshow 2000). Both HIGHD and URBCOM land use showed a strong negative relationship with the probability of PVP occurrence. The variable CROP, although also negatively related to the probability of PVP occurrence, did not show as strong a response, and the predicted probability of PVP occurrence did not fall below the $\alpha=0.53$ level until the 7853 m^2 area surrounding a point included greater than 82% crop land use.

Model Validation

The final model was tested with two new datasets, a second group of 500 PVP and 500 RP points from the original data set and a group of 706 CVP points (MassGIS 2003), to evaluate the predictive performance of the final model. Sites with a predicted probability >0.53 were considered predicted events. Results from the model validation datasets indicate that the model has good predictive performance for locating vernal pools in the landscape. The model correctly predicted 64.8% of PVPs, with 41.8% false positive predictions, while correctly predicting 441 of 706 (62.5%) CVP points within the study region.

DISCUSSION

The Massachusetts Wetland Protection Act does not specifically protect vernal pools unless they are certified by a field verification process (Kenney 1995, Burne 2001). While this is currently the best mechanism for protecting vernal pools in Massachusetts, it is still largely inefficient and does not provide protection for the upland habitat surrounding a vernal pool basin. The Rivers Protection Act protects vernal pools and upland habitat within 61 m of a perennial stream (Burne 2001). I found that only 24.6% of potential vernal pools are currently offered protection under this Act. Other regulatory mechanisms are necessary to protect the remainder of the potential vernal pools, although current regulatory mechanisms do not afford protection for the upland habitat required by many vernal pool associated organisms (Semlitsch 1998).

The model did not correctly predict the complete set of vernal pools in either the PVP or the CVP datasets.

The false positive and negative predictions of vernal pool presence could have resulted in part from the nature of the PVP data layer that was used to develop the model, as the data did not include small pools (less than 38 m diameter) or those located beneath conifer canopies and thus not visible in the aerial photographs used to derive the data layer (Burne 2001). In addition, the data layers used to derive variables in the model had varying degrees of mapping and positional accuracy and may have contributed to the false predictions of the model.

Unlike traditional techniques of locating ephemeral wetlands, a simple model such as the one presented here can determine the probability of finding an ephemeral wetland given easily-obtained landscape parameters. Despite the mapping units of the data layers being many orders of magnitude larger than the size of a vernal pool (e.g., the surficial geology mapped features at a scale of 1:250 000 with 60-m resolution), broad patterns were evident and suggest that vernal pools have unique associations with topography, glacial history, and land use of a region. These relationships are the result of complex landform effects (Swanson et al. 1998), which influence geomorphic processes and thereby influence the occurrence of a vernal pool in the landscape.

In this model, concordant with Palik et al. (2003), higher odds ratios of the surficial geology variable (GEO; Table 1) indicated a strong association between the presence of a vernal pool and the glacial history of a landscape. The probability of finding a vernal pool was positively related to the surficial geology variable, indicating that potential vernal pools are more likely to be found on sand/gravel, fine grained, and floodplain/alluvium than on the most abundant surficial geology type, till/bedrock. The application of the model is likely applicable to the glaciated northeastern United States; the use of the model outside of this landscape should be approached with caution.

I hypothesized that the land use within an area of hydrologic importance (i.e., 50 m from a point) would have the greatest influence on the presence of a potential vernal pool. Human use of the land can influence hydrology, both indirectly by altering the soil and local flowpaths and directly by changing the amount and flow direction of water. The odds ratios for the land-use parameters indicate that these variables are important, although not a dominant factor influencing the occurrence of a potential vernal pool. Land-use variables included in the model were all negatively related to the presence of a vernal pool (Figure 2). The inclusion of these variables in the model, combined with data on recent changes in land use, particularly with respect to the loss of forest cover and the increase in residential development in Massachusetts (MassGIS 2002; http://www.state.ma.us/mgis/landuse_stats.htm), indicate that the persistence of vernal pools on the landscape may be compromised if the recent trends in landscape change continue.

Interestingly, as cropland increased within the 50-m buffer around a potential vernal pool point, the probability of potential vernal pool presence was greater than expected with 100% forest cover, until the percent of cropland increased beyond 30% of the buffer area. Cultivated areas are typically restricted to areas with less steep slopes, are often supplemented with irrigation, and can result in the formation of a hardpan under the till depth over a significant period of use, influencing infiltration by affecting the macrostructure of the soil (van der Kamp et al. 2003). van der Kamp et al. (2003) found that increasing dominance of tree cover (*Salix* sp.) did not affect adjacent wetland water level, while the replacement of tilled crop land with grasses decreased the water depth in adjacent wetlands. Water level in ephemeral wetlands is influenced by tillage (Euliss and Mushet 1996), likely because mechanical alteration of the soil profiles results in simplification of hydrologic flow paths. Precipitation and runoff, primary components of the vernal pool water balance (Brooks 2004), are directed to a depression in the landscape and can result in the formation of a temporary wetland. Experimental testing of the influence of specific land-use practices on the formation of a vernal pool is needed to clarify the relationship between land-use practices and wetland formation.

Because of the importance of vernal pools to amphibians and other organisms, a model that is able to predict the locations of these habitats in the landscape can be useful in regulatory and conservation efforts. This model can be applied to a parcel of land as part of a potential biodiversity assessment and will return the probability of finding an ephemeral wetland habitat within the bounds of some defined land unit. The logistic model presented in this paper does not consider biological use of these habitats and only describes the landscape position in which vernal pools occur. In order to develop a complete and biologically pertinent model of viable vernal pool habitat, the relationship among landscape characteristics, such as spatial layout of forest habitat with vernal pool location (e.g., Semlitsch 1998), should be considered as a principal concern in conservation planning for vernal pool associated species. If animals have evolved unique associations with a habitat (Wilbur 1980), and organisms using these habitats have both low vagility (Berven and Grudzien 1990, Sinsch 1990, deMaynadier and Hunter 1999) and high site fidelity, especially in the adult life stage (Shoop 1968, Stenhouse 1985, Madison 1997), and the habitats have unique associations with large-scale variables, then protection of these habitats *in situ* is critical for the conservation of populations of these organisms. Inconsistent successes of created temporary wetland habitats underscore this point (Lehtinen and Galatowitsch 2001, Pechmann et al 2001, Campbell et al. 2002, Petranka et al. 2003).

The relationship between the occurrence of a vernal pool and the landscape variables identified in this study would be strengthened through observational and experimental testing, but these results suggest that vernal pool formation and their location in the landscape is non-random. With increasing anthropogenic pressure on the landscape, careful attention should be paid to the distribution of these habitats if the long-term persistence of populations of ephemeral wetland-associated organisms is a conservation goal.

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