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PRIMARY RESEARCH PAPER

Testing the transferability of a marsh-inundation model across two landscapes

Anhua Wei · Patricia Chow-Fraser

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Abstract The effect of water-level (WL) fluctuations on both the structure and functioning of coastal marshes is well documented, and in the past, scientists have demonstrated this by relating historical changes in the areal cover of emergent vegetation (EM) of a particular site to corresponding WL data. This approach of relating areal cover to WL cannot be applied to multiple sites from a region experiencing the same WL because in that instance, WL would be a constant and cannot be used as an explanatory variable for emergent cover. In a previous study of Cootes Paradise Marsh, we proposed the use of a Digital Elevation Model (DEM) to examine the effect of WL fluctuations on emergent plant cover over a 60-year period (1934–1993), and found that the inundated area (IA) was a better predictor of emergent cover than WL. However, the transferability of the marsh-inundation model and the related uncertainty has not yet been tested in a distinct geographic region. In the present article, we test the transferability of the model and develop a regional model of vegetation response to validate the DEM-based method. We confirm the existence of a highly significant relationship between percent IA and percent emergent cover over a large spatial scale in Eastern Lake Ontario. Additionally, we showed that this general relationship might be modified by the degree of urbanization in wetland watersheds. Our results suggest that this DEM-based approach is useful for predicting the aggregate response of EM to annual WL fluctuations and is transferable from local to regional scales.

Keywords Wetlands · Water level fluctuation · Inundation · Land use · DEM · GIS

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A. Wei (✉) · P. Chow-Fraser
Department of Biology, McMaster University, 1280 Main Street West, Hamilton, ON, Canada L8S 4K1
e-mail: weia@mcmaster.ca

Introduction

Emergent marshes located on the fringe of large lakes are a vital feature of these aquatic ecosystems because they provide food and shelter for diverse communities of waterfowl, fish, and invertebrates (Wei et al., 2004). In the Laurentian Great Lakes, change to mean WL as a result of climate change is expected to dramatically alter the community of emergent vegetation (EM) in these ecosystems, and the response pattern of these primary producers to water-level (WL) fluctuations has been extensively investigated (e.g., Lyon & Drobney, 1986; Hudon, 1997; Chow-Fraser et al., 1998; Gottgens et al., 1998; Chow-Fraser, 2005). Although consensus exists on a general negative relationship between WL change and EM at specific sites, testing for proper geographical transferability of existing WL based predictive models has usually been neglected. In recent years, there has been an increased interest in testing the transferability of ecological models in cross-regional prediction (e.g., Fielding & Haworth, 1995; Kleyer, 2002; Randin et al., 2006). This is mainly because predictive geographical modeling has recently become an important tool to access the impact of land use and other environmental change on the distribution of organisms (Guisan & Zimmermann, 2000).

The conventional way that authors have demonstrated the effect of WL fluctuations on the vegetation dynamics of a particular site is to relate changes in areal cover of EM to historical WL. While this approach has been useful for examining effects of WL disturbance at a single site over multiple years, it cannot be applied to multiple sites from a region experiencing the same WL at a given time, because in the latter case, WL is a constant, and cannot be used as an explanatory variable for EM. In this case, a WL-based model at a specific site is not transferable in space.

There is currently a great need to develop predictive models to examine the effects of different WL regimes on EM at a basin-wide scale in the Great Lakes region (Wescoat et al., 2006). The recent drop in lake levels in Lakes Huron and Michigan to near-record-low levels (NOAA Great Lakes Environmental Research Laboratory, unpublished data) has also increased the need to develop basin-wide forecasts of how wetlands in these middle lakes will respond to further declines in lake levels with anticipated climate change scenarios (Magnuson et al., 1997). Predictive models based on WL would be inappropriate for such basin-wide forecasts because of the lack of generality of the models in cross-region predictions (Williams, 1995).

In a previous study (Wei & Chow-Fraser, 2005), we proposed the use of Digital Elevation Models (DEM) to examine the effect of long-term (1934–1993) WL fluctuations on the EM of Cootes Paradise Marsh, a degraded freshwater marsh of Lake Ontario. We used the DEM to calculate a new term, called "Inundated Area" (IA), which approximated the amount of land in the wetland that is submerged. We found that the observed percentage cover of EM (hereinafter called % $\text{Emergent}_{\text{observed}}$) was significantly and negatively correlated with IA, after controlling for the effect of WL fluctuations. There was no significant correlation between % $\text{Emergent}_{\text{observed}}$ and WL after controlling for IA. The success of IA is probably because IA reflects both site-specific bathymetric characteristics and lake level. Although we concluded that the relationship among the IA, WL, and EM would be an important consideration when multiple sites from the same region are compared, the transferability of the IA–EM model, and the related uncertainty has not yet been tested in a distinct geographic region. The aim of the present study was to evaluate the transferability and quality of the IA–EM model and to propose a regional model to predict the aggregate response of emergent cover over a large spatial scale in Eastern Lake Ontario.

Methods

Study area

An independent dataset used for testing the transferability of the IA–EM model came from 10 sites located within a 28-km stretch of Eastern Lake Ontario shoreline (see Fig. 1). The mean summer WLs along the shoreline of Eastern Lake Ontario were nearly identical and the difference in mean WL recorded at the Oswego and Cape Vincent gauge stations was <1 cm. This allowed us to test the IA–EM model while 'controlling' for WL. These sites were also chosen because the amount of urbanized land in wetland watersheds was low (approximately 2%) relative to that of Cootes Paradise Marsh's 20%. Thus, the transferability of the model can be tested across two different landscapes.

Data sources

Emergent cover data for coastal wetlands of the 10 Eastern Lake Ontario were downloaded from the website (http://www.nwi.fws.gov), which is operated by the U.S. Fish and Wildlife Service. These data are part of the National Wetland Inventory (NWI) and contain digitized maps produced from aerial photos taken in 1978, corresponding to the U.S. shoreline of Eastern Lake Ontario. These maps included vegetation zones (e.g., identified as shrubs, EM, and aquatic beds) without any detailed taxonomic information.

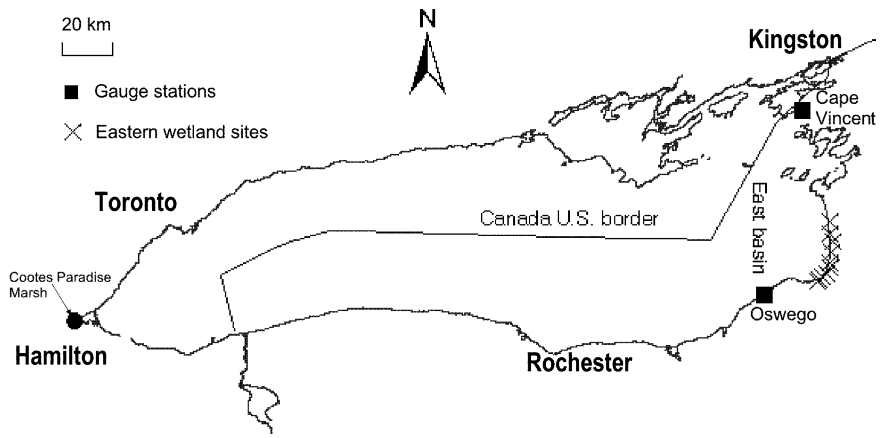

Fig. 1 Map of Lake Ontario, showing location of study sites in the eastern portion of the lake, and location of Cootes Paradise Marsh and the two water-level gauges at Oswego and Cape Vincent. Location of major cities in Canada and the U.S. are also indicated

In addition, open-water areas were also identified so that the total amount of wetland area ($TOTAL_{NWI}$) can be calculated by summing areal cover of vegetation types and open-water areas. Detailed information on the NWI wetland maps has been documented in Tiner (1999).

The 10 m DEM data were obtained from the Cornell University Geospatial Information Repository. Appropriate WLs were obtained from the National Oceanic & Atmospheric Administration (NOAA). We used land-use type as surrogate of urbanization. With the aid of land-use maps, we classified wetlands adjacent to urbanized areas as urbanized wetlands, while the rest were classified as nonurbanized wetlands.

Digital elevation model and inundated area

The core of our new approach is a DEM. A DEM has been defined as a "digital model of landform data represented as point elevation values" (DeMers, 2003). In a Geographical Information System (GIS), DEM is a digital map of elevation values over a two-dimensional grid. Inundated area can be calculated from DEM in a GIS by selecting pixels that are below a specified WL and multiplying the number of selected pixels by unit area per pixel. It can be conceptualized as the amount of "open water", as well as a small portion of the emergent cover since emergent plants often grow from the edge of upland vegetation into shallow water. Since we used the mean summer WL to calculate IA, the corresponding IA reflected the average amount of IAs for the sites.

The wetland boundary delineated from DEM (i.e., $TOTAL_{DEM}$) was determined by the highest historical WL data point. It is, therefore, different from that based on field observations, and we caution against using DEM to delineate wetland boundary for anything other than to estimate % IA.

Our approach involves the following steps: (1) Calculate IA for the sites using mean summer WLs; (2) Derive total wetland area using the DEM-based approach outlined above (i.e., $TOTAL_{DEM}$). Note that this is independent of the method based on field observations as discussed earlier, and will yield a value different from that of $TOTAL_{NWI;}$ (3) Calculate the proportion of IA to $TOTAL_{DEM}$ (i.e., % IA). Note that we calculated % IA by dividing IA by the total wetland area derived by DEM rather than by field observations (i.e., $TOTAL_{NWI}$), to avoid a potential spurious relationship introduced by a shared term (i.e., X/Z vs. Y/Z) (Jackson & Somers, 1991; Brett, 2004); (4) Run a regression with permutation test to examine the relationship between % Emergent cover and % IA.

Some other calculations in this study are summarized as follows:

(a) $\%\ \text{Emergent}_{\text{potential}} = (\text{Emergent}_{\text{potential}} / \text{TOTAL}_{\text{DEM}}) \times 100$

(c) $\%\ \text{Emergent}_{\text{observed}} = (\text{Emergent}_{\text{observed}} / \text{TOTAL}_{\text{field}}) \times 100,$

where $\text{Emergent}_{\text{observed}}$ is the observed areal cover of EM determined from vegetation maps and/or aerial photos, and $\text{TOTAL}_{\text{field}}$ is the total wetland area calculated from field observations.

Data analysis

We used ESRI ArcGIS 8.1 to estimate IA by applying corresponding WL data to DEMs of Cootes Paradise and Eastern Lake Ontario. Regression with permutation test was performed in REGRESSN (Program for multiple linear regression with permutation test by Pierre Legendre, Universite de Montreal). Dutilleul's modified *t*-test was performed in PASSAGE v 1.1 to control for the presence of spatial autocorrelation and deterministic structures (e.g., linear gradient from east to west) in the data.

We tested and evaluated the transferability of the IA–EM model by examining an independent data set from 10 sites in Eastern Lake Ontario. The predictive success of the IA–EM model was then evaluated by calculating the coefficient of determination (R^2) between the predictions and the observations, as suggested in Guisan and Zimmermann (2000).

Results

Wei & Chow-Fraser (2005) indicated that IA alone explained 83.1% of variation in the observed percentage of emergent cover in Cootes Paradise Marsh. To make it directly comparable to % IA calculated for wetlands from Eastern Lake Ontario, we reanalyzed the data from Cootes Paradise Marsh and converted IA to % IA by dividing IA by wetland boundary derived from the DEM ($r^2 = 0.831$). In the case of a single site study such as Cootes Paradise Marsh, conversion of IA to % IA did not change the response of % $\text{Emergent}_{\text{observed}}$ ($r^2 = 0.831$).

As mentioned from the outset, the relationship between WL and % $\text{Emergent}_{\text{observed}}$ cannot be established for multiple sites in a large geographical area when they experience the same summer mean WL or similar WL with little variation. However, corresponding IA at these sites are likely to be very different due to variation in site topography, and could be used to predict the response of EM. To test the transferability of the model to a distinct geographical area, we calculated % $\text{Emergent}_{\text{predicted}}$ using the predictive model developed in Cootes Paradise marsh, and % $\text{Emergent}_{\text{observed}}$ using an independent dataset from Eastern Lake Ontario. We found that the relationship between % $\text{Emergent}_{\text{predicted}}$ and % $\text{Emergent}_{\text{observed}}$ was statistically significant (Fig. 2a, $r^2 = 0.537$, $P = 0.016$).

Theoretically, % $\text{Emergent}_{\text{observed}}$ and % IA should be negatively correlated because as the proportion of IA in a wetland increases, proportionately greater hydrological stress will limit the colonization of emergent plants, and the % $\text{Emergent}_{\text{observed}}$ will be smaller. Percent $\text{Emergent}_{\text{observed}}$ in these marshes was regressed against corresponding % IA to test this assumption. We found a significant negative relationship between % IA and % $\text{Emergent}_{\text{observed}}$ (Fig 2b, $r^2 = 0.54$, n = 10, $P = 0.018$; Dutilleul's modified *t*-test; geographically effective sample size 7, $P = 0.049$), confirming that % IA is a good predictor of the proportion of EM in coastal wetlands that share the same or similar WL.

For other wetland systems where wetland boundaries are difficult to delineate based on field observations, the potential emergent habitat based

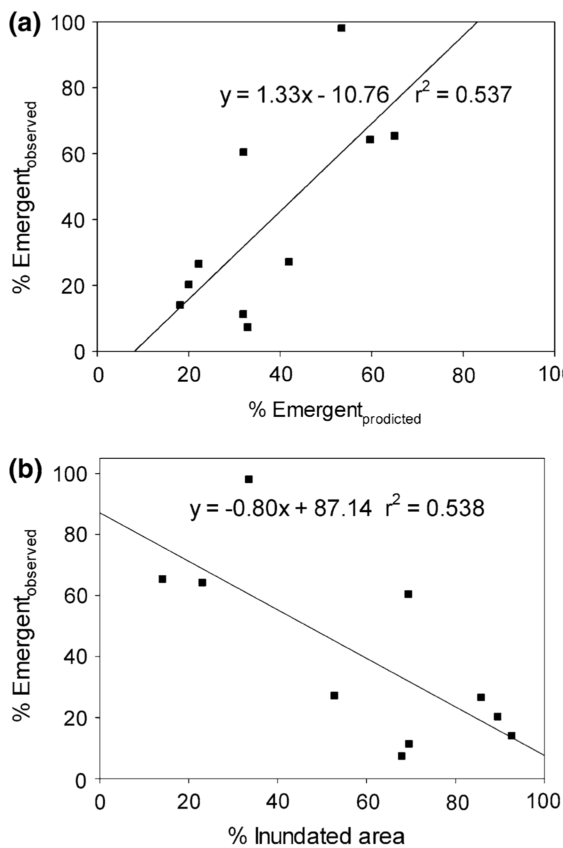

Fig. 2 Regressions of % $\text{Emergent}_{\text{observed}}$ against (**a**) % $\text{Emergent}_{\text{predicted}}$ and (**b**) % inundated area for Eastern Lake Ontario wetlands

on DEM and WL information could be used to predict % $Emergent_{observed}$ (Fig. 3). The potential habitat area, which we have called $Emergent_{potential}$, can be roughly estimated by determining the area of the marsh between the high and low watermarks, and is conceptualized as the amount of habitat released by low WLs. Five values for $Emergent_{observed}$ in Fig. 3b were underestimated because the DEM for Eastern Lake Ontario did not include elevations below 75 m.a.s.l, and this resulted in underestimating some observed areas for EM since both % IA and % $Emergent_{potential}$ are based on calculated IA.

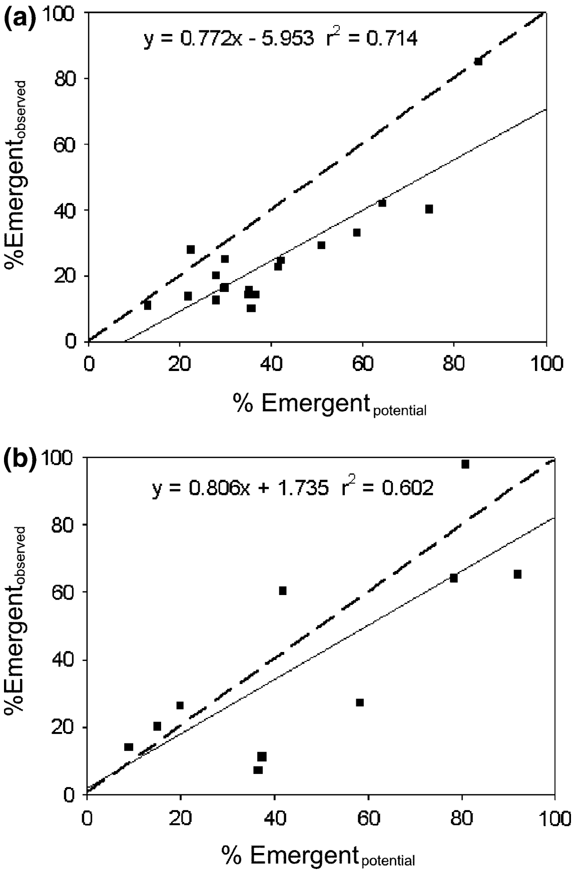

Fig. 3 Relationship between % observed emergent vegetation (% $Emergent_{observed}$) based on vegetation maps and % potential habitat occupied by emergent vegetation (% $Emergent_{potential}$) (based on DEM information) for (**a**) Cootes Paradise, and (**b**) Eastern Lake Ontario. The broken line shows y = x. The solid line is the regression line for the data points. In both cases, there is a general trend toward lower than expected emergent cover based on water depth information (i.e., application of WL to DEM data)

The effects of urbanization on EM vary according to urbanization level (Table 1). For Cootes Paradise Marsh, % IA alone explained 83.1% of variation in % $Emergent_{observed}$. Inclusion of human population as a surrogate for urbanization explained another 4% of variation in % $Emergent_{observed}$, and the effect of urbanization was highly significant (Table 1a). For Eastern Lake Ontario wetlands, a dummy variable (urbanized vs. nonurbanized) was used to evaluate the effect of urbanization. We used this variable as a surrogate for urbanization because human population data were not available, and found a significant relationship between % $Emergent_{observed}$ and % IA, but no significant effect of urbanization, probably due to the crude surrogate for urbanization and the low statistical power (Table 1b).

Discussion

One of the main aims of this study was to assess the transferability of the marsh-inundation model outside the region, for which the model was developed. Randin et al. (2006) suggested that transferability of a predictive model and the related uncertainty should be estimated first, before the model is to be projected in space or time. Some authors recommend using a geographically independent dataset for a proper evaluation of models (e.g., Fielding & Haworth, 1995; Guisan & Zimmermann, 2000; Randin et al., 2006).

It was apparent from Fig. 2a that the prediction was successful although the predictive power of the model decreased when the model developed in Cootes Paradise marsh was applied to a different landscape in Eastern Lake Ontario. Nevertheless, Fig. 2b indicated that % IA was still a good predictor of EM on a regional scale.

Randin et al. (2006) suggested that the quality of the predictor variables could affect transferability of models. Although there is some vertical uncertainty (e.g., measured errors) in the DEM of Eastern Lake Ontario, this is unlikely to decrease predictive power of the marsh-inundation model because the comparison of % $Emergent_{observed}$ and % $Emergent_{predicted}$ is not related to the DEM of Eastern Lake Ontario (Fig. 2a). However, the vertical uncertainty of the DEM could affect the regional model shown in Fig. 2b. Thus, very high resolution DEM (e.g., DEM

Table 1 Summary of multiple regressions relating % Emergent$_{observed}$ to % IA and land-use change

Term	Coefficients	Std error	t Ratio	Prob > |t|
(a) *Highly urbanized Cootes Paradise Marsh* (R^2 = 0.873, *n* = 20, *P* = 0.001)				
Intercept	91.91	10.20		0.000
% inundated area	−0.48	−6.40	0.00	0.000
Human population	−0.75	−2.39	0.02	0.014
(b) *Low urbanized wetlands in Eastern Lake Ontario* (R^2 = 0.599, *n* = 10, *P* = 0.043)				
Intercept	97.22	4.96		0.001
% inundated area	−1.17	−2.64	0.01	0.017
Land use	24.45	1.04	0.16	0.167

derived from LIDAR data. LIDAR is an acronym for Light Detection And Ranging) could improve the approach proposed in this study.

The independent data in this study were collected from Eastern Lake Ontario. In contrast to Cootes Paradise Marsh's 20%, the urbanization within the watersheds of the 10 sites from Eastern Lake Ontario is relatively low, approximately 2%. The difference in land use between western Lake Ontario and Eastern Lake Ontario could affect the transferability of the model (Randin et al., 2006).

The quality of response variables could be a methodological issue with transferability and this has usually been neglected. Like many other studies at a large geographical scale, seasonal variation may affect the data quality. Some of the EM data in this study might be collected in different seasons and the errors related to seasonal variation could account partially for the decreased predictive power of the model.

Our finding that there is a general pattern in the aggregate response of EM to WL disturbance has important implications for wetland research and management. Whereas in the past, digital bathymetric data were more difficult to obtain than historic wetland maps, it will soon become the reverse as more and more government-sponsored digital libraries become available on line. This will make it a relatively simple task to calculate IA, the potential habitat for emergent plants in any wetland, along with the amount of urbanized area in its associated watershed. The generalized approach that we have provided here could become a very useful management tool to assess the basin-wide response of emergent marshes to WL disturbances caused either by lake-level regulation or by global climate change scenarios.

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