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Primary Research Paper

Untangling the confounding effects of urbanization and high water level on the cover of emergent vegetation in Cootes Paradise Marsh, a degraded coastal wetland of Lake Ontario

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Abstract

An approach based on a digital elevation model (DEM) was used to untangle the confounding effects of long-term water-level fluctuations and increasing human population on the cover of emergent vegetation in Cootes Paradise Marsh, a degraded coastal wetland in Lake Ontario, Canada. Data for 20 observations between 1934 and 1993 were used in the analysis. First, we calculated the inundated area based on the DEM, a derived measurement that reflected the bathymetry of the marsh and the mean water level for a particular year. Then Mantel correlations and regression analyses were used to analyze the relationships between emergent cover and corresponding water level, inundated area, and human population, respectively. Results of the simple and partial correlations indicated that areal change of emergent plants was significantly correlated with inundated area after controlling for the effect of water level fluctuation; however, there was no significant correlation between emergent cover and water level after controlling for inundated area. This is an important consideration when multiple sites from the same Great Lake are compared since the same water level may correspond to vastly different inundated areas for different marshes. Changes in emergent cover were also significantly correlated with human population after controlling for water level effects. Altogether, inundated area explained 83.1% of the variation, human population explained 4.2%, and the interaction between population and inundated area explained an additional 4.3% of the remaining variation in areal emergent cover. This indicates that the synergistic effect of high water level (expressed as inundated area) and increased human population induced greater detrimental impact on the emergent plants than did either stressor alone.

Introduction

Emergent marshes along the shores of the Laurentian Great Lakes play an important ecological role in stabilizing the substrate, providing habitat for fish, amphibians, invertebrates, birds, and mammals, replenishing dissolved oxygen concentration in the water column, and sequestering nutrients from the sediment. Their cyclical expansion and contraction are well documented, and many studies have confirmed the negative relationship between percentage cover of emergent vegetation and increased lake elevation (e.g. Lyon et al., 1986; Keddy & Reznicek, 1986; Williams, 1995; Hudon, 1997; Williams & Lyon, 1997; Chow-Fraser et al., 1998; Gottgens et al., 1998). In urbanized wetlands such as Cootes Paradise Marsh, the dramatic reduction in emergent cover has taken place over six decades of increasing anthropogenic disturbance (e.g. nutrient enrichment from sewage effluent, hydrologic modification, and increased runoff from agricultural and urban development in the watershed (Chow-Fraser et al., 1998; Chow-Fraser, 2004). Since both increased water level and nutrient enrichment can negatively affect the establishment of a large number of emergent taxa in experimental microcosms (Weiher et al., 1996), it is possible that factors other than high water level (e.g. cultural eutrophication) have been responsible for the loss of emergent vegetation in this and other wetlands in developed areas of the Great Lakes shoreline (e.g. Frenchman's Bay in Eyles et al., 2003).

A number of equations have been published that relate areal emergent cover to water level on a site-specific basis (e.g. Lyon et al., 1986; Hudon, 1997; Chow-Fraser et al., 1998); however, these equations have rarely been applied to other wetlands because the effect of water level depends on marsh bathymetry that can differ greatly from site to site within one Great Lake. Thus, despite the accumulation of historic vegetation maps for several marshes (e.g. Williams, 1995; Chow-Fraser et al., 1998; Wilcox et al., 2003), a regional model of vegetation response has not emerged, primarily because no study has yet been conducted that statistically relate emergent cover to the actual depth of inundation.

An effective way to quantify the amount of inundated area of a particular wetland is to apply water-level scenarios to a detailed bathymetric map of the wetland. With the advent of geographic information systems (GIS) and widespread availability of satellite data, digital elevation models (DEMs) can now be used in conjunction with lake elevation data to calculate area of inundation. This approach has been used to simulate the effects of flooding in rivers (e.g. Vining, 2002), but has rarely been used in studies of water-level effects on wetland succession. In this paper, we propose to use this approach to investigate the response of emergent vegetation to simultaneous changes in water level and anthropogenic disturbance in the watershed of Cootes Paradise Marsh over 60 years of observations. First, we will use a DEM to quantify the amount of inundated area for 20 different water-level scenarios from 1934 to 1993, and then we will assess how the amount of inundated area and human population growth has contributed separately and synergistically to the corresponding decline in marsh vegetation. Our approach should be generally applicable to other wetlands and should eventually lead to the generation of an aggregate response of emergent vegetation to water level fluctuations at a regional or basin-wide scale.

Method

Study site

Cootes Paradise is a 250-ha coastal wetland, located at the west end of Hamilton Harbour, a natural embayment at the west end of Lake Ontario (Fig. 1). Since the marsh is managed as a nature reserve, only non-motorized boats/canoes are permitted access, and there is no recreational fishing. Cootes Paradise is drained by three main tributaries: Spencer Creek, Borer's Creek, and Chedok Creek. It receives runoff from adjacent agricultural, residential, industrial, commercial, and recreational lands, as well as effluent from the Dundas Sewage Treatment Plant. It is surrounded by the city of Hamilton to the south, and the towns of Ancaster, Dundas and Flamborough to the north and west. The major natural disturbance is interannual and seasonal fluctuations in water level of Lake Ontario (Chow-Fraser, 2004). In general, water level rises in the spring, peaks in May or June, and recedes in the autumn, reaching its lowest level in December. Prior to the last century, almost 100% of Cootes Paradise was covered with emergent plants, but sustained high water depths from the 1930s to the1980s have contributed to a dramatic decline of emergent cover approaching 10% by the 1990s (Chow-Fraser et al., 1998; Chow-Fraser, 2004). Historical changes in the percentage cover of the major species of emergent plants in Cootes Paradise Marsh during the years of observation are shown in Table 1. Under a high water level of 75.4 m, the marsh has a mean depth of 0.93 m (Fig. 2).

Data

The percentage cover of emergent vegetation (EM) between 1934 and 1993 were taken from Chow-Fraser et al. (1998). These data were obtained from several sources: historical aerial photographs and historical vegetation maps stored in the Royal Botanical Garden. The historical vegetation maps

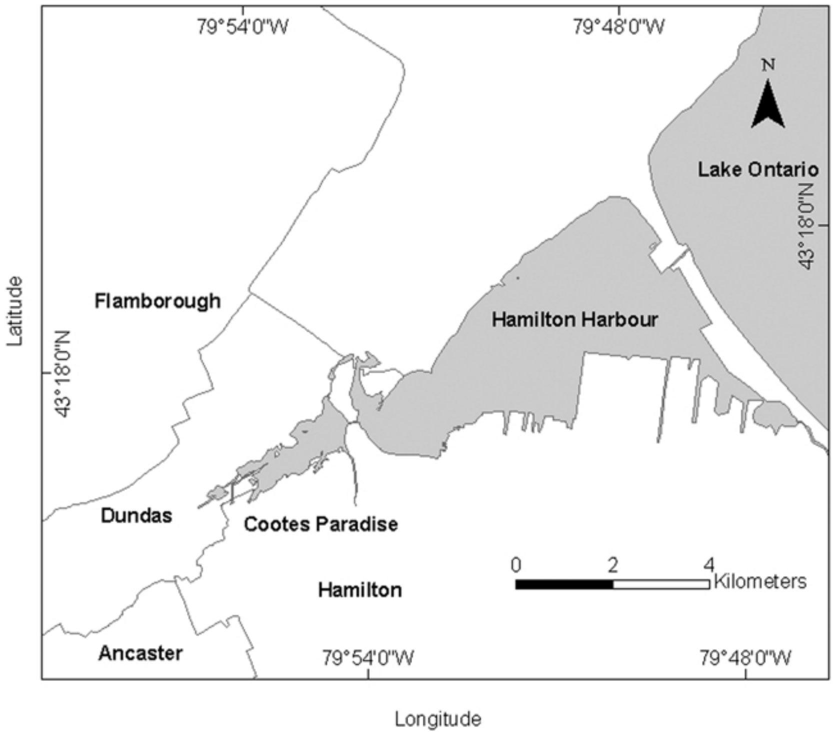

Figure 1. Location of Cootes Paradise Marsh, Hamilton Harbour and the surrounding city of Hamilton, and towns of Ancaster, Dundas and Flamborough.

Table 1. Historical changes in the percentage cover of the major species of emergent plants in Cootes Paradise Marsh during the years of observation

Major species	1946	1953	1971	1974	1975	1977	1978	1979
Typha latifolia	24.0	4.0	3.6	0.3	0.4	0.6	1.7	1.2
Glyceria maxima	14.7	4.3	15.4	5.2	8.9	6.8	9.1	10.7
Sparganium eurycarpum	0.3	0.3	0.0	0.0	0.2	0.0	0.5	1.0
Nymphaea tuberosa	0.2	1.6	0.1	0.1	0.0	0.0	0.0	0.1
Bidens cernua	0.0	1.7	0.2	0.3	3.4	6.4	1.4	0.3
Phragmites australis	0.0	0.0	1.0	0.2	0.2	0.1	0.1	0.1

for years 1946, 1953, 1971, 1974, 1975, 1977, 1978, and 1979 were available in a GIS format. Detailed descriptions of the sources of data and data processing are documented in Chow-Fraser et al. (1998).

Since water quality data were not available for early years, historical census population data (POP) were used as a surrogate of potential cultural eutrophication. Data for the Hamilton–Wentworth region (including Hamilton, Dundas, Ancaster, and Flamborough shown in Fig. 1) were obtained from Statistics Canada and Ontario Ministry of Revenue. The data for several missing years were estimated from a regression equation: $\text{Population} = -30.647 \cdot \text{year}^2 + 8098.8 \cdot \text{year} - 31950$, $r^2 = 0.9931$.

Water-level (WL) data for Cootes Paradise were estimated by applying a formula developed by Chow-Fraser et al. (1998) to continuous water-level data measured at Station 13150 in Burlington, Ontario. The formula was : $\text{WL (C)} = 1.038\ (\pm 0.029) \cdot \text{WL (B)} - 2.802$, $n = 38$,

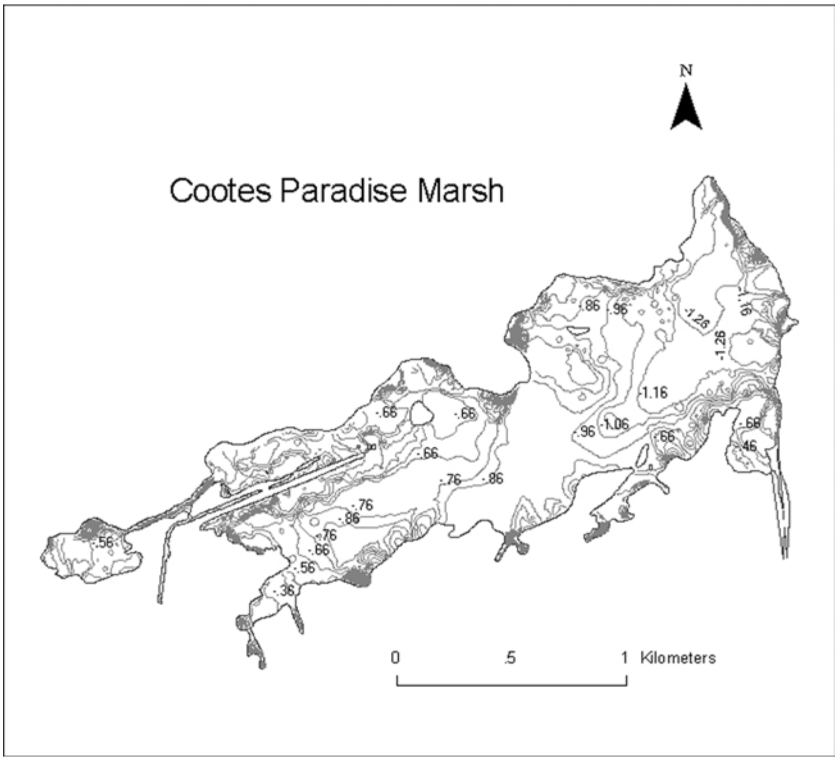

Figure 2. A bathymetric map of Cootes Paradise Marsh.

$r^2 = 0.88$, $p = 0.0001$, where WL (C) and WL (B) are the water levels (m, a.s.l.) for Cootes Paradise and Burlington, respectively.

Inundated areas (IA) for the corresponding mean summer (May to September inclusive) water levels for different years were estimated using the DEM of Cootes Paradise in ESRI ArcGIS 8.1 (http://www.esri.com). The DEM was produced from Painter et al.'s (1989) contour map and a DEM provided by the Ontario Ministry of Natural Resources (OMNR; M. Robertson, Peterborough, Ontario, Canada). Since the contour map only provided depth information for 75.06 m a.s.l. and site elevations greater than 75.06 m were not available, a seamless merge with OMNR's elevation points was required. We digitized the contour map using its scanned map, and then re-sampled 2300 water depth values from the contour map. The overlapping area was removed from OMNR's DEM before it was merged with the re-sampled points from the contour map. The final DEM was interpolated from the combined elevation points using Spatial Analyst in ESRI ArcGIS 8.1. The cell size of the DEM was 10 m. Wise (2000) provides a comprehensive review of approaches to assess DEM quality and suggests that the best judge of the adequacy of a DEM is the level of accuracy for the intended purpose. We assessed the accuracy of the DEM using two sets of field-measured data. The first set consists of 21 points with known water depths and coordinates that were collected in summer of 2003. We found no significant differences in mean water depth between the DEM and the field data when difference in the means was set to 5 cm (paired *t*-test, $p = 0.15$, two-tailed). The second dataset was the historical vegetation maps for years 1946, 1953, 1971, 1974, 1975, 1977, 1978, and 1979. The DEM would be adequate for this study if the inundated areas derived from the DEM do not differ significantly from the measured open-water areas corresponding to the digitized vegetation maps. Theoretically, in a wetland with abundant emergent plants, the inundated areas should be larger than the observed open-water areas. Based on this assumption, we set the difference in the mean areas to be 10%, and we found no significant difference between calculated inundated areas and measured open-water areas (paired t-test; $p = 0.14$, two-tailed). Therefore, both analyses indicated that our DEM is hydrologically accurate for Cootes Paradise Marsh and is acceptable for the proposed use in this study (see Fig. 2 for a bathymetric map derived from the DEM).

Statistical analysis

We performed a simple Mantel test and a partial Mantel test using S-plus 2000 and zt (Bonnet & Peer, 2002) to assess the correlations among water level, inundated area, census population, and emergent cover. The Mantel test used here is a statistical test that has been widely applied in population genetics, ecology, anthropology, psychometry, and sociology (Legendre, 2000). The simple Mantel test is an examination of the relationship between two distance matrices. The partial Mantel test estimates the correlation between two matrices while controlling for the effect of a third matrix (i.e. one variable is held constant) (Lengendre & Legendre, 1998) and it is used to remove potential spurious relationships. Regression analyses were performed in SAS JMP 5.1.

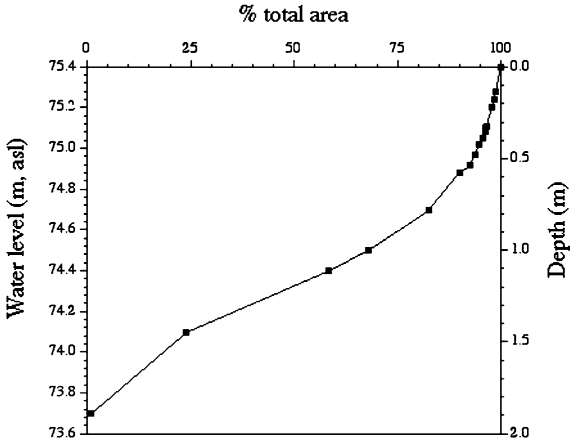

Figure 3. Hypsographic curve of Cootes Paradise marsh.

Results

The hypsographic curve of Cootes Paradise marsh in Figure 3 describes the relationship between the surface area of marsh contours and lake elevation or depth. According to this relationship, the range of water-level conditions that have been encountered in a high-water year (75.3 m) such as that encountered in 1993 would correspond to IA of 99%, while a low-water year such as that encountered in 1946 (74.4 m) would correspond to only 58% of the total marsh area. This confirms the great impact that water-level fluctuations must have exerted on the emergent vegetation through the six decades of observations (Fig. 4).

EM was significantly regressed against WL, POP, and IA (Fig. 4a–c, respectively; Table 2). Of these, IA was the strongest predictor of EM, explaining 3.3% more of the unexplained variation than did WL, and 26.2% more than did POP. A simple Mantel correlation r measures the extent to which variations in distances of a variable (e.g. WL) correspond to variations in another variable (e.g. EM), while the partial Mantel test estimates the correlation between the two matrices while controlling for the effect of a third matrix (Fig. 5). Results of both tests are displayed in tabular form in Figure 5. Correlation coefficients for the Mantel are displayed above the diagonal, while those for the partial Mantel test are displayed below.

All coefficients of the Mantel tests for WL, IA, and EM were significant (values in bold in Fig. 5a). However, the partial correlation coefficient of 0.1653 (Fig. 5a) indicates that after controlling for effects of IA, WL was no longer significantly correlated with EM. By contrast, the coefficient 0.3785 (Fig. 5a) indicates that IA was significantly correlated with EM, after controlling for variations in WL. Not surprisingly, the correlation between WL and IA was significant ($r = 0.9427$) and even after accounting for variations in EM ($r = 0.7980$) (Fig. 5a). These results support the causal model in which WL causes changes in IA and which then causes changes in EM (flow diagram in Fig. 5a).

Next, we performed a similar analysis with IA, EM, and POP (Fig. 5b). We omitted WL from the analysis because IA, which incorporates the effects of WL and bathymetric characteristics, was shown to have greater explanatory power. Both IA and POP were significantly correlated with emergent cover when the partial Mantel tests were performed (0.8071 and 0.4710, respectively; Fig. 5b).

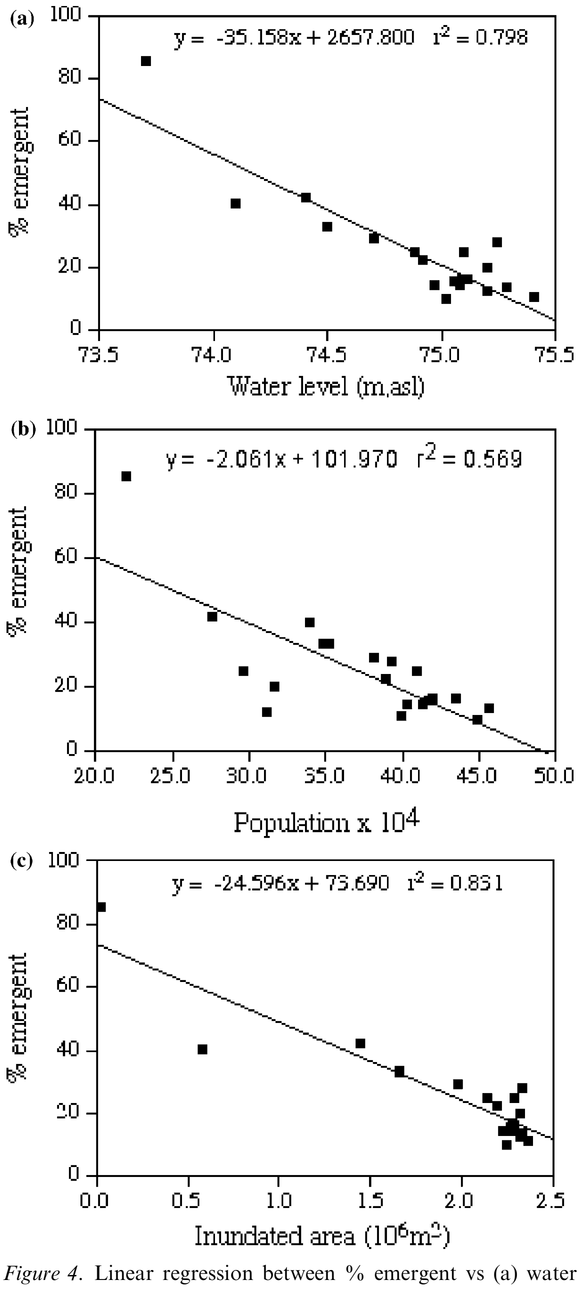

Figure 4. Linear regression between % emergent vs (a) water level (m, a.s.l.), (b) population census and (c) inundated area for Cootes Paradise from 1934 to 1993.

This is consistent with results of the regression analyses in Figure 4, and supports a causal model in which both IA and POP can affect the percentage cover of EM in Cootes Paradise Marsh (flow diagram in Fig. 5b). Figure 5c is a combined causal model that reflects the results of all Mantel correlation coefficients. This model indicates that the effects of WL on EM are indirect, since IA, which takes into account the unique bathymetry of the wetland, has the most direct effect. On the other hand, POP appears to have a direct link to EM as well.

Table 2. Regression analyses (n = 20)

Dependent variable	Term	Coefficient	SE	t	p
EM	Intercept	2657.80	312.38	8.51	< 0.0001
	WL	−35.16	4.172	−8.43	< 0.0001
EM	Intercept	101.97	15.91	6.41	< 0.0001
	POP	−2.06	0.42	−4.87	0.0001
EM	Intercept	73.69	5.37	13.73	< 0.0001
	IA	−24.60	2.61	−9.41	< 0.0001
EM	Intercept	76.84	9.20	8.35	< 0.0001
	IA	−11.91	3.77	−3.16	0.0061
	POP	−0.81	0.26	−3.09	0.0070
	(IA−1.96)* (POP−37.11)	0.89	0.31	2.86	0.0113

To determine the relative power of each explanatory variable for predicting variation in EM, we performed a stepwise regression analysis with IA, WL, and POP. AI explained 83.1% of the total variation (p = 0.0001) while POP explained an additional 4.2 % (p = 0.0308), but addition of WL did not explain any more of the residual variation ($p = 0.4117$). We then performed a multiple regression analysis with IA, POP, and IA*POP (interactive term between the two independent variables). This model was highly significant (p = 0.0001), and was accompanied by an improved R^2-value of 0.916 compared with a model that does not include the interactive term. Each of the independent variables explained a significant amount of the variation in EM, as did the interactive term, POP*IA (Table 2). This analysis indicates that the synergistic effect of total inundated area and increased human population induced greater detrimental impact on emergent plants than did either stressor alone.

Discussion

An important finding in this study is that WL showed no significant correlation with EM, after controlling for the confounding effects of IA; in

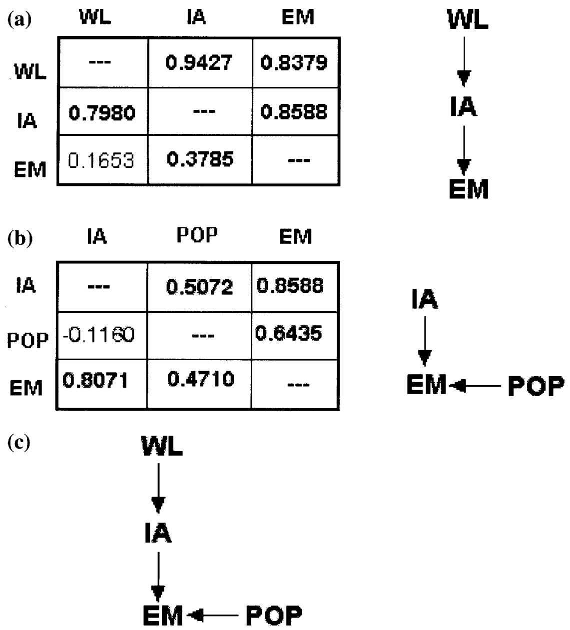

Figure 5. Mantel correlations between matrices for (a) water level (WL), inundated area (IA), and emergent cover (EM), and (b) inundated area, emergent cover and census population (POP). Causal models are presented to the right of the matrices. Correlations in bold indicate significance at $\alpha = 0.05$.

contrast, when the effect of WL was controlled, IA still showed a significant correlation with EM (Fig. 5). This confirms that IA is a better predictor than WL for EM since the former reflects both site-specific bathymetric characteristics and lake level. Another important finding is that increased human population in the region had a significant negative effect on the cover of emergent vegetation in Cootes Paradise Marsh. Previous studies have confirmed the linkage between the levels of land-use alteration and the changes in aquatic ecosystems (e.g. Euliss et al., 1996; Booth et al., 1997; Wang et al., 2000). Euliss et al. examined the influence of landscape condition on water-level fluctuations in wetlands in the Prairie Pothole Region of North and South Dakota, and concluded that water-level fluctuations are greater in wetlands located in areas of intensive agricultural activity relative to those in more natural grassland settings. Taylor (1993, cited in Schueler, 1994) suggested that additional storm water due to the effect of watershed development and increase in imperviousness contribute to greater annual water level fluctuations on 19 freshwater wetlands in King County, Washington. In general, urbanization increases runoff due to increased impermeable surfaces such as rooftops, roadways, and sidewalks because the greater the population there is in a region, the greater the need there is for residential, commercial, industrial, institutional, agricultural, and transportation. The significant negative effect of increased human population on emergent plants in Cootes Paradise Marsh implied that increased impervious surfaces due to increased human population in the region also contribute to the greater water level fluctuations and eventually cause detrimental effect on the emergent vegetation in Cootes Paradise Marsh.

In addition to greater water level fluctuations, increased runoff often result in increased loadings of nutrients, toxic substances such as heavy metals, pesticides, oils, road salts, and detergents into waterways (Wang et al., 2000), which may have detrimental effects on aquatic vegetation (Owen, 1999). On a regional basis, Grosslink & Baumann (1980, cited in Mitsch & Grosslink, 2000) also found that loss rate of coastal wetlands was closely related to population density in the USA from 1954 to 1974.

In the case of Cootes Paradise Marsh, increase in the surrounding population also meant an increase in phosphorus loading since effluent from the Dundas Sewage Treatment facility has been discharged directly into the marsh for over 8 decades (Chow-Fraser et al., 1998). Even though sewage effluent is no longer an important source of external phosphorus load to the marsh, there is a great deal of accumulated phosphorus in the sediment that continues to be released during the summer, and thus maintains the overall hypereutrophic state of the wetland (Kelton et al., 2004). The inundation of previously terrestrial soils by increasing water levels can also lead to an increase in available nitrate via increased denitrification. Weiher et al. (1996) have shown that emergent taxa such as *Typha* are unable to become established in enriched sediments even in drawdown conditions, although more can survive when they are exposed to slightly inundated but infertile sediments. Even though water depth and soil fertility are two dominant factors, there may be other important factors, such as wave actions and bioturbation (Chow-Fraser, 1998), and these should be investigated as appropriate.

Conclusion

The distribution of emergent plants is a function of many factors including water level, bathymetry, nutrients, competitive interactions among plants Kellogg et al., 2003), and bioturbation (e.g. carp). We have shown that inundated area (a measure derived from DEM that reflects the bathymetry of the marsh and the mean water level for a particular year) as well as the population size of the region are significant predictors of the percentage cover of emergent vegetation in Cootes Paradise Marsh, explaining close to 92% of the variation. Mantel correlations indicate an overall causal model in which emergent plant cover is directly affected by both inundated area and population size, and where water level indirectly affects emergent vegetation by regulating the amount of inundated area. Cultural eutrophication, as a consequence of urbanization, contributes measurable negative impact on the aquatic habitat and can interact with natural disturbances such as high water levels to accelerate marsh degradation.

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