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Influence of increasing populations of Double-crested Cormorants on soil nutrient characteristics of nesting islands in western Lake Erie

Scott A. Rush [a,*], Stephanie Verkoeyen [a], Tammy Dobbie [b], Sandy Dobbyn [c], Craig E. Hebert [d], Joel Gagnon [a], Aaron T. Fisk [a]

[a] *Great Lakes Institute for Environmental Research, 401 Sunset Avenue, University of Windsor, Windsor, N9B 3P4, Ontario, Canada*
[b] *Point Pelee National Park, 407 Monarch Lane, RR 1, Leamington, N8H 3V4, Ontario, Canada*
[c] *Ontario Parks, Southwest Zone, 659 Exeter Road, London, N6A 4L6, Ontario, Canada*
[d] *Wildlife and Landscape Science Directorate, National Wildlife Research Centre, Carleton University, Raven Road, Ottawa, K1A OH3, Ontario, Canada*

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ABSTRACT

Animals can influence the structure of an ecosystem by changing the levels of nutrient input. This is of particular importance for the islands of western Lake Erie, which are relatively nutrient poor, but have experienced increases in nutrient input from growing double-crested cormorant (*Phalacrocorax auritus*) populations. The objectives of this study were to evaluate changes in soil characteristics (nutrients [nitrate (NO_3), total P], pH, and $\delta^{13}C$ [as a tracer of cormorant-associated nutrients]) across a gradient of cormorant nest density on two islands (Middle and East Sister) in western Lake Erie. For both islands, soil pH decreased and P concentrations increased with nest density. On Middle Island, soil nitrate concentrations increased with cormorant nest density, and varied with breeding phenology, with highest concentrations during the early and mid nesting season ($272 \pm 19\ \mu g\ g^{-1}$) and lowest concentrations late in the season ($165 \pm 11\ \mu g\ g^{-1}$). Following a 3-year absence of nesting activity at sites on Middle Island, soil nitrate concentrations were similar to those at low density sites. In contrast, nitrate concentrations measured on East Sister Island did not correlate with temporal or spatial patterns of cormorant nesting and remained elevated 10 years post-cormorant use. While the results of this study confirm that chronic input of allochthonous materials alters soil properties of these islands, the unique conditions of each island must be considered when predicting ecological effects and setting long-term management objectives.

Introduction

Animals can influence the structure of an ecosystem by changing nutrient dynamics (Polis et al., 1997; Schindler and Scheuerell, 2002; Fukami et al., 2006). For instance, during the breeding season, waterbirds that feed aquatically often deposit food scraps, guano, eggshells, feathers, and bodies of dead chicks and adults within the terrestrial environments of their nesting colonies (Sanchez-Piñero and Polis, 2000; Sekercioglu, 2006). The input of such allochthonous materials to terrestrial ecosystems can substantially alter soil nutrient content and properties, plant species diversity, and biological community composition (Hobara et al., 2001; Ellis et al., 2006; Kameda et al., 2006).

Input of avian-derived nutrients has been implicated in alteration of biochemical nitrogen (N) cycling in littoral ecosystems (Hobara et al., 2001; Mizota, 2009) and soils beneath waterbird colonies may be characterized by elevated nutrient levels and lower pH (Hebert et al., 2005). Within these systems, moderately elevated levels of N and phosphorous (P) are expected to increase plant growth and productivity (Smith, 1978). The presence of excess amounts, however, can result in toxicity to plant species and has been implicated in habitat changes occurring across some terrestrial systems (Hebert et al., 2005; Ellis et al., 2006).

The magnitude of avian effects on terrestrial systems is however also influenced by the density of their nests (Hebert et al., 2005; Alisauskas et al., 2006). Within North America's Laurentian Great Lakes region, double-crested cormorant (*Phalacrocorax auritus*) populations have increased greatly in size and range over the past several decades (Weseloh et al., 1995; Hebert et al., 2005, 2008). Associated with this population expansion, the density of nesting cormorants has also increased prompting concern about potential impacts on littoral forest ecosystems (Kamstra et al., 1995; Hebert et al., 2005). Although nest density is likely to influence the effects of cormorants on terrestrial habitats, few studies have quantitatively compared soil nutrients across a gradient of nest densities (Ellis, 2005).

The objectives of this study were to examine the effects of cormorant density on soil characteristics (nitrate (NO_3), total P, and pH) on two islands (Middle and East Sister) in the western basin of Lake

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* Corresponding author. Tel.: +1 216 904 2439 (cell).
E-mail address: srush@uwindsor.ca (S.A. Rush).

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Erie. Stable isotopes of carbon [δ^{13}C] were also assessed in the soil to confirm the transfer of nutrients from aquatic sources to terrestrial soils via the deposition of cormorant guano. We also evaluated whether soil NO_3 and P concentrations responded to seasonal changes in cormorant densities on each island. Our working hypotheses were that cormorant nesting activities would result in the addition of nutrients, such as NO_3 and P to soils, with greatest deposition occurring during the peak of the breeding season and in areas where cormorant nest densities were high. We also anticipated soil NO_3 concentrations would track seasonal nutrient deposition patterns by cormorants, i.e. soil NO_3 concentrations would peak in mid-season and decrease following breeding activities (Gilliam et al., 2001). Unlike NO_3 concentrations, we predicted that soil P concentrations would show little temporal variability.

Material and methods

Study area

Field sampling took place on Middle Island (18 ha) and East Sister Island (15 ha) in western Lake Erie (Fig. 1). Cormorants first colonized East Sister Island in 1981 and Middle Island in 1987, with nesting colonies experiencing substantial growth during the following 10-year period (Hebert et al., 2005). At present, major habitat types on both East Sister and Middle islands include unvegetated rocky shoreline, open wetlands, and wet and mesic forests (Boerner, 1984; Kamstra et al., 1995), supporting >20 provincially rare species (T. Dobbie and S. Dobbyn, unpublished data). Island soils are composed of decaying organic matter, silt loams and limy glacial till shallowly covering bedrock of mostly dolomite and limestone (Tracey, 1971; Boerner, 1984; Kamstra et al., 1995). These islands are characterized by little relief with rock exposures occurring only at the shoreline. Minor rock outcrops occur frequently on the north and southwest shores, and infrequently along the south and eastern shores.

The climate of the islands of western Lake Erie is temperate with conditions buffered by lake effects (Boerner, 1984). January and February are the coldest months (*c.* −3.5–0.5 °C; 1996–2008 monthly averages: NOAA, unpublished data), whereas June through August are the warmest (*c.* 20–23.5 °C; 1996–2008 monthly averages: NOAA, unpublished data). The islands receive ≥750 mm of precipitation each year (Boerner, 1984). Unlike Middle Island, East Sister Island supports a small (<1 ha) emergent wetland, with portions of the island seasonally inundated by vernal pools.

Cormorants nest in colonies from April through August (Hatch and Weseloh, 1999). Although cormorants nest on the ground in other areas (Hatch and Weseloh, 1999), all active cormorant nests on East Sister and Middle islands have been exclusively in trees with densities varying across the tree-covered portions of the islands (Hebert et al., 2005). While other colony-nesting species do occur on Middle and East Sister islands (ring-billed gull (*Larus delawarensis*), herring gull (*Larus argentatus*), great blue heron (*Ardea herodias*), great egret (*Ardea alba*), and black-crowned night-heron (*Nycticorax nycticorax*)), the total number of these nests per year was less than 9 × the number of double-crested cormorant nests (T. Dobbie and S. Dobbyn, unpublished data). Therefore, we assumed that these other species did not contribute greatly to soil chemistry.

Sample collection

Soil samples were collected from marked locations on each island (East Sister Island $n=19$; Middle Island $n=25$; Fig. 1) from 2007–2009. Nest densities were quantified at all soil sampling locations on East Sister and Middle islands during July 2009, reflecting the height of cormorant nesting activities. On each island the number of cormorant nests was counted within a 10 m radius centered on each soil sample location. Several additional sites (East Sister, $n=4$; Middle Island, $n=5$) were identified on each island as areas where cormorants no longer nested (hereafter referred to as post sites). On Middle Island, the last nesting records of cormorants in post sites occurred in 2006, however, on East Sister Island, cormorants were last known to nest in post areas >10 years prior to this study (S. Dobbyn and T. Dobbie, pers. observation). Although cormorant nest densities were determined within 10 m radii, for clarity we provide estimates as nests ha^{-1}.

Cormorant nesting activities can vary markedly at different stages of the breeding season (Hatch and Weseloh, 1999). Soil sampling, conducted during 2007–2009, reflected this breeding phenology, which we define as: 1) early (April–May), 2) mid (June–July), and 3) late (August–October). Soil sampling was carried out once during each period in 2008 and 2009 and only during the mid and late periods in 2007. During each sampling period, one soil sample was collected from each marked location. Forest floor litter was removed prior to sampling and soil samples were collected using a hand trowel, from the O horizon, to a depth of approximately 5 cm. Soil samples were stored in plastic bags and refrigerated upon returning to the lab.

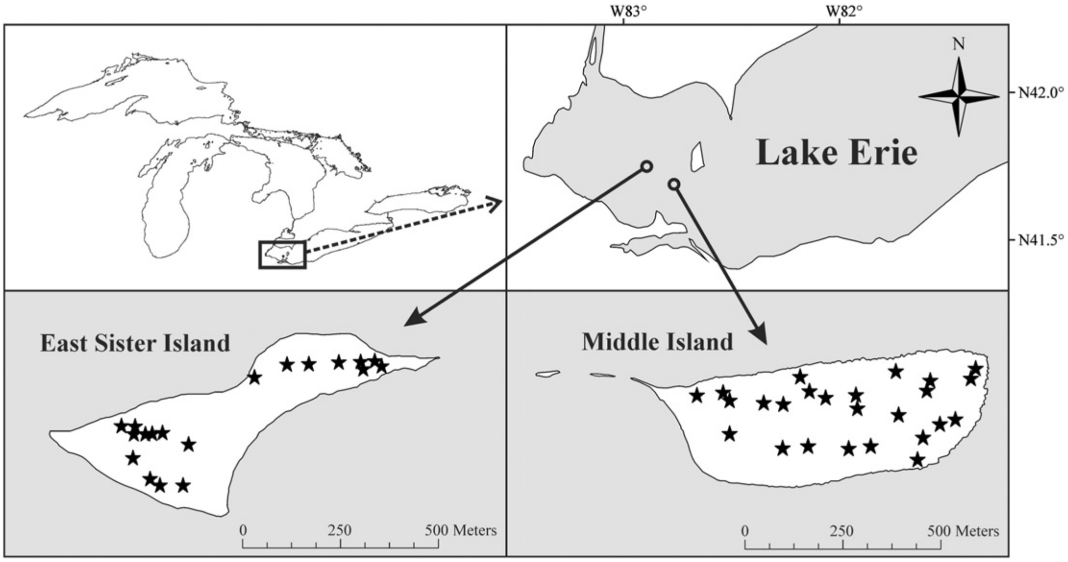

Fig. 1. Map of islands in Lake Erie. Stars indicate locations of soil sampling.

Soil nutrients and pH

For nitrate analysis, 4 g of each wet-weight soil was placed in a flask and 20 mL of 2 M KCl solution was added. Flasks were filtered and the filtrate was analyzed using Alpkem continuous-flow colorimetry. For analysis of total P, 25 mg of each dry, ground sample was weighed and transferred to a digestion tube, whereupon 500 uL diH2O, 500 uL of 5.5 M H_2SO_4 and 0.20 g of $K_2S_2O_8$ were added to each tube. Afterwards, the tubes were autoclaved for 1 h. Once cooled, the contents of the digestion tube were rinsed into a scintillation vial with 15 mL diH_2O and allowed to settle overnight. The next day, 5.0 mL of solution from the scintillation vial was mixed with 10.0 mL of acid matrix (K_2SO_4–H_2SO_4 solution). The solutions were then analyzed using Alpkem continuous-flow colorimetry. The dry sample contents were calculated from measured dilute extract values (Nelson, 1987). The pH of all soil samples was determined using a LaMotte Soil Test Kit (LaMotte, Chesterton, Maryland, USA).

Isotopic analysis

Soil samples were freeze-dried using a Labconco 4.5 freeze-dryer with a Thermo Savant ModulyoD ice condenser and LyoPump vacuum pump. Approximately 2.5 to 4.0 mg of each dried sample was weighed into tin capsules for the determination of $\delta^{13}C$. Isotope ratios were determined using a Thermo Finnigan DeltaPlus Mass Spectrometer equipped with an elemental analyzer. Stable isotope abundances are expressed in delta notation (δ) in per mil units (‰). The analytical precision for $\delta^{13}C$ was estimated to be 0.06‰ based on the standard deviation of replicate analyses of NIST 8414 standard (bovine muscle, $n=16$), which was run with all samples.

Statistical analysis

Our sampling design incorporated multiple seasons and locations. We therefore used several statistical methods to evaluate potential relationships between cormorant nest densities and soil properties between islands, across seasons, and among years. Probability plots (R Development Core Team, 2009) indicated that pH, NO_3 and P data were not normally distributed. Because these data were not normally distributed they were log(x) transformed prior to analysis. Values of $\delta^{13}C$ were log(x) transformed after adding a value equal to the positive equivalent of the minimum value. Levene's tests indicated that the variance of $\delta^{13}C$ was unequal between islands ($P<0.02$). Therefore, including only those sites that continued to support nesting cormorants, we evaluated differences in soil $\delta^{13}C$ between East Sister and Middle islands using t-tests, assuming unequal variance (R Development Core Team, 2009). The influence of cormorant nest densities on total P and nitrate concentrations, pH, and $\delta^{13}C$ values in soil were evaluated within and between islands using analysis of covariance models. Using planned orthogonal contrasts (R Development Core Team, 2009), soil pH, $\delta^{13}C$, nitrate, and P concentrations were compared between sites characterized by low nest densities (1 to 100 nests ha^{-1}) and those categorized as one of the following nest densities: post, absent (absence of cormorant nests), medium (101 to 300 nests ha^{-1}), and high (>301 nests ha^{-1}). We used likelihood-ratio tests to identify differences in relationships between islands.

We assessed the influence of breeding period on soil nitrate concentrations by applying 2-level linear mixed-effects models (LMEs). Mixed effects models were fit using restricted maximum likelihood in R (version 2.7.1: R Development Core Team, 2009). In our 2-level model the top level was represented by year, and the lowest level of the model represented the error term or the individual soil observations. As cormorant nest densities were anticipated to decrease across the nesting season (Ewins et al., 1995), we evaluated soil nutrient concentrations by treating year as a random effect (random intercept) and breeding period (e.g., early, mid and late) as a fixed effect. For each LME, we applied planned, orthogonal linear contrasts, using *glht* in the R package *multcomp* (version 2.7.1: R Development Core Team, 2009), to compare soil attributes (P and NO_3) between the different breeding periods (early vs. mid, mid vs. late, and early vs. late: Hothorn et al., 2008). For all analyses, differences were considered significant if $P<0.05$.

Results

During April 2009, the density of cormorant nests within 10 m of soil sampling plots was higher on East Sister Island than on Middle Island (East Sister mean: 333.16 nests ha^{-1}; Middle Island mean: 146.42 nests ha^{-1}; $t_{41}=2.5$, $P<0.02$). This difference in cormorant nest density was reflected in a stronger signature of lentic-derived materials on East Sister Island, which was manifested by the lower $\delta^{13}C$ of soils sampled on this island (East Sister mean: −26.2; Middle Island mean: −23.1; $t_{41}=-4.16$, $P<0.01$; Table 1). Soil pH decreased with increased cormorant nest density ($t_{33}=-4.04$, $P<0.01$), a relationship that did not differ between islands ($X^2=1.21$, $P=0.55$). Soil P concentrations increased with increased cormorant nest density ($t_{33}=4.77$, $P<0.001$) in samples collected from both islands ($X^2=2.02$, $P=0.15$). For East Sister Island, there was no evidence that soil $\delta^{13}C$ ($F_{1,13}=0.59$, $P=0.45$), or soil nitrate concentration ($t_{13}=1.48$, $P=0.16$) varied with nest density. On Middle Island, soil $\delta^{13}C$ ($t_{18}=-2.11$, $P=0.05$) was negatively correlated, and nitrate concentration ($t_{18}=2.86$, $P=0.01$: Fig. 2) was positively correlated with nest density. On East Sister, nitrate concentrations did not differ between post sites and areas with active cormorant nests (Table 1).

Soil nitrate concentrations on East Sister Island did not vary seasonally (early vs. mid: $Z_1=-0.09$, $P=0.43$; mid vs. late: $Z_1=0.74$,

Table 1
Soil characteristics by cormorant nest density category for two islands in western Lake Erie collected in 2009. Values represent mean ± SE.

Island	Density (range of nest densities: nests ha^{-1})	n	pH	$\delta^{13}C$	NO_3 ($\mu g\ g^{-1}$)	P ($\mu g\ g^{-1}$)
East Sister Island	low[a] (31–64)	3	6.8 ± 0.3	−26.48 ± 0.07	134.28 ± 10.25	1.34 ± 0.05
	medium[b] (127–286)	6	6.6 ± 0.2	−26.19 ± 0.32	302.8 ± 95.56	1.42 ± 0.17
	high[c] (318–605)	6	6.1 ± 0.3	−26.27 ± 0.15	214.55 ± 48.14	2.11 ± 0.19
	post[d]	4	6.8 ± 0.1	−26.05 ± 0.39	105.9 ± 24.56	1.31 ± 0.04
Middle Island	absent[e]	7	7.5 ± 0	−22.36 ± 1.12	175.7 ± 19.13	0.57 ± 0.03
	low[b] (32–96)	5	7.1 ± 0.2	−23.29 ± 1.08	280.62 ± 36.69	1.28 ± 0.35
	medium[c] (127–255)	5	6.2 ± 0.3	−23.39 ± 1.98	331.86 ± 182.09	1.85 ± 0.43
	high[d] (446–541)	3	6.3 ± 0.2	−25.41 ± 0.09	790.2 ± 456.14	2.47 ± 0.32
	post[f]	5	6.8 ± 0.1	−25.00 ± 0.24	323.02 ± 93.14	1.26 ± 0.02

[a] (1 to 100 nests ha^{-1}).
[b] (101 to 300 nests ha^{-1}).
[c] (>300 nests ha^{-1}).
[d] (0 nests ha^{-1}), absence of nesting cormorants for >10 years prior.
[e] (0 nests ha^{-1}).
[f] (0 nests ha^{-1}), absence of nesting cormorants for three years prior.

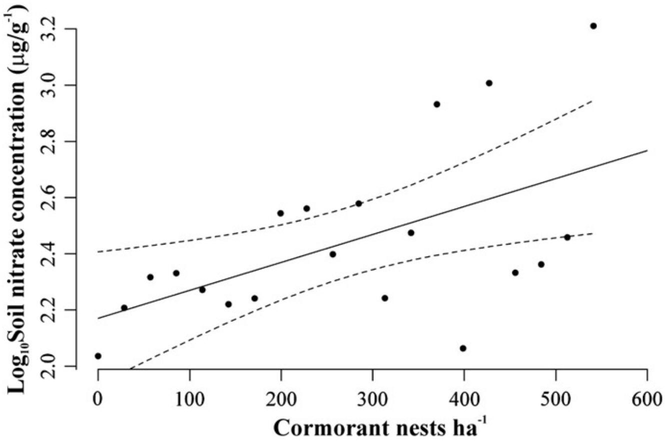

Fig. 2. Soil nitrate concentrations measured on Middle Island in April, 2009. Solid line depicts the relationships between soil nutrient concentrations and cormorant nest density (log[nitrate concentration (μg g^{-1})]~2.17 + 0.03(SE: 0.01) nests/m^2: R^2 = 0.30). Dashed lines represent 95% confidence intervals.

$P = 0.73$; early vs. late: $Z_1 = 0.26$, $P = 0.47$) and there was no difference in soil P concentrations among seasons on either island ($P > 0.05$). In contrast, we found some seasonal variation in soil nitrate concentrations on Middle Island. Here, lowest concentrations occurred during the late season (early vs. late: $Z_1 = 3.12$, $P < 0.001$). Although there was some evidence that nitrate concentrations differed between mid and late, this relationship was not statistically significant (mid vs. late: $Z_1 = 2.28$, $P = 0.06$).

Discussion

Nesting double-crested cormorants have influenced the soil characteristics of two small islands (<20 ha.) in the western basin of Lake Erie. Soil P concentrations increased and pH decreased with increasing numbers of cormorant nests on both islands, while nitrate increased with nest density on Middle Island only. Furthermore, altered soil characteristics can persist in some areas where cormorants no longer nest.

The link between the aquatic systems of Lake Erie, where the double-crested cormorants feed (Stapanian et al., 2002), and the deposition of materials on these islands was confirmed by the more negative δ^{13}C values measured in soils below cormorant nests. Interestingly, between the two islands sampled, δ^{13}C values were lower in soil from all sites on East Sister Island (Table 1). One explanation for this result is that the lentic-derived carbon input to East Sister was proportionally greater than to Middle Island. The lower δ^{13}C values of the East Sister Island soils could also reflect that these soils are naturally more ^{13}C-depleted, thus masking the influence of lentic-derived materials on δ^{13}C values.

Despite higher cormorant nest densities on East Sister Island, and δ^{13}C values that suggest greater lentic input to this island, the highest concentrations of NO_3 and P were found on Middle Island (Table 1). Differences in NO_3 and P concentrations between islands could relate to heterogeneity in the soil characteristics and vegetative communities of these two islands (see Kamstra et al., 1995). For instance, whereas nitrate concentrations in Middle Island soils were positively related to cormorant nest density, cormorant nest density was a poor predictor of soil nitrate concentrations on East Sister Island.

The historical use of these islands by nesting cormorants may also influence nutrient distributions. We observed differences between islands in terms of seasonal patterns of soil nutrient concentrations (Table 1), and between areas with active cormorant nests and those where cormorants no longer nested. East Sister Island, as compared with Middle Island, has experienced a longer duration of cormorant nesting activity and, as a result, may have received a greater cumulative deposition of cormorant guano.

While other colonial nesting species use these islands, their nest densities were considerably less than the density of double-crested cormorants. Although these species also contribute allocthonous materials to these terrestrial systems, the greater density of cormorant nests likely contributes more materials to smaller areas. Cormorant nesting colonies may therefore represent short-term, high nutrient inputs that can affect the nutrient status of the land as well as the surrounding ecosystems (Ellis, 2005). For instance, the accumulation of NO_3 in soils can promote the potential for increased losses to leaching (Groffman et al., 1993; Hanson et al., 1994; Aber et al., 1998; Gilliam et al., 2001). The leaching of nutrients from forest soils can cause other ecological changes extending beyond areas receiving nutrient inputs, altering biological communities both on the island and in the surrounding lake ecosystem (Ludsin et al., 2001; Boegman et al., 2008). Therefore, additional studies will be required to assess the ecological importance and implications of the continued transfer of materials by cormorants to these island systems.

Altered nutrient dynamics may play an important role in regulating plant communities. Within most ecosystems, moderate nutrient additions are expected to increase plant growth and productivity (Smith, 1978; Brumme and Khanna, 2007). Excess NO_3 and P, such as found under seabird colonies, can inhibit growth or change species composition (Ellis, 2005; Hebert et al., 2005). For instance, Ishida (1997) and Ellis et al. (2006) found that cormorant-derived nutrients lowered seed germination in impacted soils. Although the results of our study document changes in the ecology of island soils, the permanence of these changes and their implications for surrounding ecosystems remains uncertain. Therefore, continued monitoring paired with *ex situ* experiments will be needed. These analyses must consider additional forms of nitrogen, such as ammonia, to evaluate long-term effects of nesting cormorants on these island ecosystems. Assessing ecological change recovery will require an integrated monitoring program including assessment of abiotic (e.g. nutrient dynamics, changes in island microclimate as a result of habitat alterations) and biotic (cormorant nest numbers, plant community status) factors. Further research on these islands will improve our understanding of factors regulating ecological resilience and the potential for ecological restoration of degraded ecosystems.

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