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The biogeochemical implications of massive gull flocks at landfills

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ABSTRACT

Gulls have long been observed concentrating in flocks of tens to hundreds of thousands at the anthropogenic food sources provided by landfills. Yet, the biogeochemical implications of the landfill gull phenomenon have been largely ignored. This study has two goals: 1) to understand the magnitude and geographic extent of landfill gulls in North America, and 2) to quantify the amount of carbon (C), nitrogen (N), and phosphorus (P) transported from landfills to gull roosting sites in order to understand their potential impacts on water quality and methane (CH_4) emission. We synthesized and mapped data from the eBird Citizen Science database and found that 1.4 million gulls have been documented at landfills throughout North America, though the actual population is probably greater than 5 million. Using a carnivorous bird transport model we estimate that these gulls transport 39,000 to 139,000 kg of P and 240,000 to 858,000 kg of N y^{-1} to neighboring water bodies and avoid roughly 1.1 to 3.9 Tg y^{-1} of landfill CH_4 emissions. The avoided CH_4 emission mitigation is insignificant in the context of gross landfill emissions, but the transported nutrients may be relevant to water quality management at local and continental scales. For example, at the Jordan Lake reservoir in North Carolina, a flock of 49,000 Ring-billed Gulls (*Larus delawarensis*) annually deposits landfill feces containing 1070 kg P, an amount equivalent to approximately half of total maximum daily load reduction targets and worth roughly $2.2 million USD in nutrient credits. We estimate that continent-wide gull impacts are worth at least $100 million in nutrient offset credits. We conclude that mega-flocks of landfill gulls are common and widespread, and that their capacity to transport nutrients may be contributing to the eutrophication of aquatic ecosystems and water supplies.

1. Introduction

Inland populations of gulls (Laridae) have increased dramatically in Europe and North America over the past century (Belant, 1997; Kadlec and Drury, 1968) primarily because of their capacity to exploit anthropogenic food sources, such as landfills (Belant et al., 1998, 1995; Burger, 1981; Horton et al., 1983; Sol et al., 1995). The concentration of gulls feeding at landfills has been an ongoing concern because of nuisance (to landfill workers and nearby residents), the hazard posed to overflying aircraft, the potential for transmission of diseases, and the degradation of water quality of ponds, lakes and reservoirs. Although evidence for the transmission of harmful bacteria, such as *E. coli* and *salmonella*, to water supplies has been documented (Alderisio and Deluca, 1999; Benton et al., 1983; Gould and Fletcher, 1978), there has been little investigation into the capacity for gulls to transport significant quantities of nutrients into freshwater bodies (but see Marion et al., 1994; Portnoy, 1990). The question remains as to whether gull-transported nutrients from landfills may compromise the quality of an adjacent water supply. Furthermore, there has been no discussion of any other biogeochemical implications of large gull flocks at landfills.

Birds have been long recognized for their function as nutrient vectors, or 'resource linkers' (Sekercioglu, 2006), but the transport of landfill trash has not been the subject of any such bird studies. These scavengers may also play an unrecognized role at landfills as trash sorters, selectively removing organic refuse that would otherwise contribute to landfill emissions of methane (CH_4), which accounts for 18% of CH_4 emissions in the United States (US Environmental Protection Agency, 2016). Landfills are intensively managed and regulated to control their biogeochemical impacts, such as requirements for impervious base lining to prevent leaching into water supplies and landfill gas collection to mitigate CH_4

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emissions. And yet, the biogeochemical consequences of bird diversion of municipal waste into adjacent ecosystems have largely been ignored.

We hypothesize that: 1) gulls transport significant amounts of nutrients from landfills to roosting sites at neighboring waterbodies; and 2) removal of labile organic C from landfills by gulls will reduce methane emissions. In this paper we synthesize and summarize the status of gull populations at landfills across North America to provide a context for the geographic scale and gross magnitude of these birds' biogeochemical impacts. We test these hypothesized impacts by modeling their magnitude at a continental scale as well as for a localized overwintering gull mega-flock that feeds at a landfill and roosts on a reservoir in the Piedmont of North Carolina.

2. Methods

2.1. North American landfill gull counts

We used the eBird citizen science database (Sullivan et al., 2009) to quantify and map gulls of 7 gull species known to concentrate at landfills in the United States and Canada: Herring Gull (*Larus argentatus*), Ring-billed Gull (*Larus delawarensis*), California Gull (*Larus californicus*), Great Black-backed Gull (*Larus marinus*), Glaucous-winged Gull (*Larus glaucescens*), Western Gull (*Larus occidentalis*), Laughing Gull (*Leucophaeus atricilla*), and Franklin's Gull (*Leucophaeus pipixcan*). We excluded all data pertaining to observations of less than 500 individuals of any of the above species and used only the highest count of each species for each locality. We searched among locality names for the terms “Landfill” and “Dump” to pull out observations directly associated with landfills. Many landfills have multiple names and/or multiple similarly-named hotspots, so we manually removed such replicates (keeping the highest counts for each species) to avoid double-counting. We mapped the sum of all gull species high counts for each site using ARCGIS based on the associated eBird hotspot coordinates.

We observed that eBird data for many landfill gull flocks is not associated with a landfill hotspot, but instead a nearby roosting site (e.g. North Wake Landfill and Falls Lake). So in order to understand the spatial distribution of inland gull concentrations far from most marine and lacustrine natural food sources, we mapped all gull counts of greater than 5000 birds at inland locations (defined as anywhere more than 50 km from a coastline or a Great Lakes water body). We excluded Franklin's Gull from this analysis as this species often concentrates in huge numbers (>100,000) during fall migration without any documented connection to landfill use.

To test the eBird data set for completeness, we conducted an informal survey on the North American Gulls Facebook group, a closed group which includes more than 4000 members from the United States and Canada who have an interest in gull watching and identification. We asked the group members to provide names and locations of landfills where they have observed 1000 or more gulls and compared their responses to the list of landfills generated from eBird data. We used the proportion of missing landfill sites to estimate the extent to which the eBird data captures the total amount of landfills where gulls have been observed.

2.2. North Carolina site descriptions

The US Army Corps of Engineers (USACE) constructed B. Everett Jordan Dam in the central Piedmont of North Carolina in 1974, which allowed the formation of a lake by the same name (subsequently referred to as “Jordan Lake”). The lake basin was flooded to its present size of 5640 ha in 1983 and has historically been one of the most eutrophic reservoirs in North Carolina due to excess N and P loads (Division of Water Quality/NC Department of Environment and Natural Resources, 2007). Starting in 1990 it began being utilized as a water source for nearby populations, especially the rapidly growing municipalities of Cary and Apex in Wake County. Total maximum daily load (TMDL) calculations are mandated by the US Environmental Protection Agency for all impaired water bodies, for which Jordan Lake is divided into three sub-watersheds: Haw River, Upper New Hope, and Lower New Hope (Division of Water Quality/NC Department of Environment and Natural Resources, 2007). USACE continues to own and operate the lake and dam.

Nearby Falls Lake has a history that largely parallels that of Jordan Lake. Its dam was built by USACE from 1978 to 1981 after which the 5022 ha lake basin was flooded. Falls Lake provides drinking water to over 500,000 residents of Raleigh-Durham. It is listed on the 303 (d) list of impaired waterbodies due to high chlorophyll concentrations and turbidity. N and P are considered to be co-limiting in Falls Lake (Lin and Li, 2011), and current nutrient reduction targets call for 40% and 78% decreases in N and P loading, respectively (North Carolina Rules Review Commission, 2011).

The South Wake Landfill (35.676181°, −78.851314°), located approximately 16 km as the gull flies east of the roosting area at Jordan Lake, opened in 2008 and processes 363 to 408 Tg y^{-1} of municipal solid waste and has an expected lifetime of 35 years (Fig. 1). The North Wake Landfill (35.907534°, −78.579411°), located 17 km southeast of the gull roosting area of Falls Lake, closed in 2008 after storing 5.5 Pg of waste during a 22-year lifespan.

2.3. North Carolina gull counts

We used Christmas Bird Count data (National Audubon Society, 2010) from the Jordan Lake and Falls Lake count circles to track population trends of gulls at two major reservoirs in the Research Triangle region of North Carolina. Ring-billed Gull make up 99% of the regional gull population, so other species are not considered. For both these counts, gulls were counted at first light at roost, while flying overhead in streams of V-shaped flocks toward foraging sites, and/or in evening after returning to roost (Brian Bockhahn, Tom Krakauer, Norman Budnitz, pers. comm.). At Jordan Lake a second observer frequently made independent estimates of the flock (Norm Budnitz, pers. comm.). With a few exceptions, the same observer has been the primary estimator of gulls at Jordan Lake from 2002 through 2014 (Tom Krakauer, pers. comm.) and the same observer has counted gulls at Falls Lake every year since 1998 (Brian Bockhahn, pers. comm.).

2.4. Fecal analysis

We visited the South Wake Landfill to collect 20 gull feces samples on 30 January 2014 after freshly fallen snow to avoid contamination with soil or trash. We stored samples at −20 C before oven drying, weighing and grinding. Three samples were dominated by a pliable plastic-like substance that would not grind and were excluded from further analysis. We analyzed the remaining 17 samples for total C and N content using an elemental analyzer (CE Instruments, Wigan, UK) and for total phosphorus using nitric-perchloric digestion and the molydenate blue spectrophotometric method (Wetzel and Likens, 2000).

2.5. Biogeochemical modeling

We estimate gull transport of nutrients from landfill to roosting site using Hahn et al. (2007) model for nutrient transport by carnivorous birds. For model calculations we assume (*L. delwarensis*) have a mean mass of 518.5 g (Pollet et al., 2012),

Fig. 1. Ring-billed Gull (*Larus delawarensis*) flock at South Wake Landfill in Wake County, North Carolina USA on 10 February 2016. This photo contains roughly 10,000 birds, approximately one-fifth of the mean number estimated during recent Christmas Bird Counts. Photo by RSW.

corresponding to a daily energy intake requirement of 737 kJ (Nagy et al., 1999). We assume a food energy content of 23.9 kJ g^{-1}, metabolizable energy coefficient of 0.76 (Karasov, 1990), and an intake:excretion ratio of 0.395 (Dobrowolski et al., 1993; Marion et al., 1994; Nixon and Oviatt, 1973). We assume a 9-h foraging day based on day-length in Raleigh, North Carolina on January 1, a gull defecation rate of 3.1 droppings h^{-1} (Gwiazda, 1996; Portnoy, 1990) and a gut retention time of 5.3 h (Hilton et al., 2000, 1999). For N and P content, we use the mean of gull fecal samples we collected at the South Wake Landfill. We assume the gull flock is present at the landfill for 120 days each year.

To estimate avoided CH_4 emissions provided by gulls, in addition to many of the same assumptions mentioned above for the nutrient transport model, a C content of gull food of 0.4 based on the stoichiometric ratio and molar masses of CH_2O, and a lab-generated CH_4 conversion efficiency of 0.33 (Bogner and Spokas, 1993).

3. Results

3.1. Large inland and/or landfill-based North American gull flocks

Gull count data from eBird documents the presence of roughly 1.4 million gulls at North American landfills. Flocks of at least 1000 gulls have been documented at 205 landfills in 37 of the 49 continental United States as well as 8 Canadian provinces (Fig. 2). Landfill gulls are dominated by Ring-billed Gull (36.8%), Herring Gull (29.2%) and Laughing Gull (20.0%). California Gulls represent 7.6% and other species each represent less than 2% of counted gulls at landfills. Weighting gull counts by published mass (Rodewald, 2015) reveals that Herring Gull is actually most important species, representing 46.6% of total landfill gull mass. The 1.4 million gulls collectively weigh roughly 940 Mg.

Generally, landfills that attract gulls appear to be concentrated along coastlines and around the Great Lakes, though there are many exceptions to this pattern. eBird data also show large concentrations of inland gulls that do not completely overlap with the landfill gulls data set. Such bird flocks are either: 1) subsisting on natural inland food sources, 2) subsisting on landfill food, but the eBird data is not associated with a landfill hotspot, or 3) subsisting on some other anthropogenic food source. Large inland gull flocks appear to be absent from Appalachia, the arid Southwest and much of the Great Plains.

The gull flock at the South Wake Landfill is unusually large for a site so far inland. Of the 9 landfills in which flock size has been estimated to be greater than 25,000 gulls, South Wake is the only site more than 65 km away from salt water. Tunica Landfill in Mississippi with 24,000 gulls and lying 100s of km from the Gulf of Mexico is perhaps South Wake's best analogue. Gulls most likely ‘discover’ food sources at Tunica, South Wake and other inland landfills by following river systems. Tunica Landfill lies just 8 km from the banks of the Mississippi River. Jordan Lake, where the South Wake Landfill gull flock is known to roost, drains into the Cape Fear River.

Out of 21 landfills identified by the North American Gulls Facebook group, eight did not have an associated eBird hotspot, or were associated with a nearby hotspot (gull roosting site) without the words ‘landfill’ or ‘dump’ in the hotspot title. This result suggests that one-third, or more, of the landfills that are observed by birdwatchers may not have any directly associated eBird data.

3.2. North Carolina piedmont gull counts

The 37-year Christmas Bird Count record for Jordan Lake shows that prior to 1989, gulls were relatively scarce, with counts never exceeding 1500 (Fig. 3). From 1992 onwards counts never dropped below 1000 and were often greater than 5000, but gull numbers exploded in 2008 with the opening of the South Wake Landfill and recent counts have consistently exceeded 40,000. For biogeochemical calculations we use the most recent five-year mean flock size from 2010 to 2014 of 49,000. The shorter, 16-year Christmas Bird Count record from the Falls Lake shows less dramatic changes in gull populations. The closing of the North Wake Landfill in 2008 does appear to have reduced gull counts compared to earlier levels, but a flock varying from 5000 to 15,000 birds persists to the

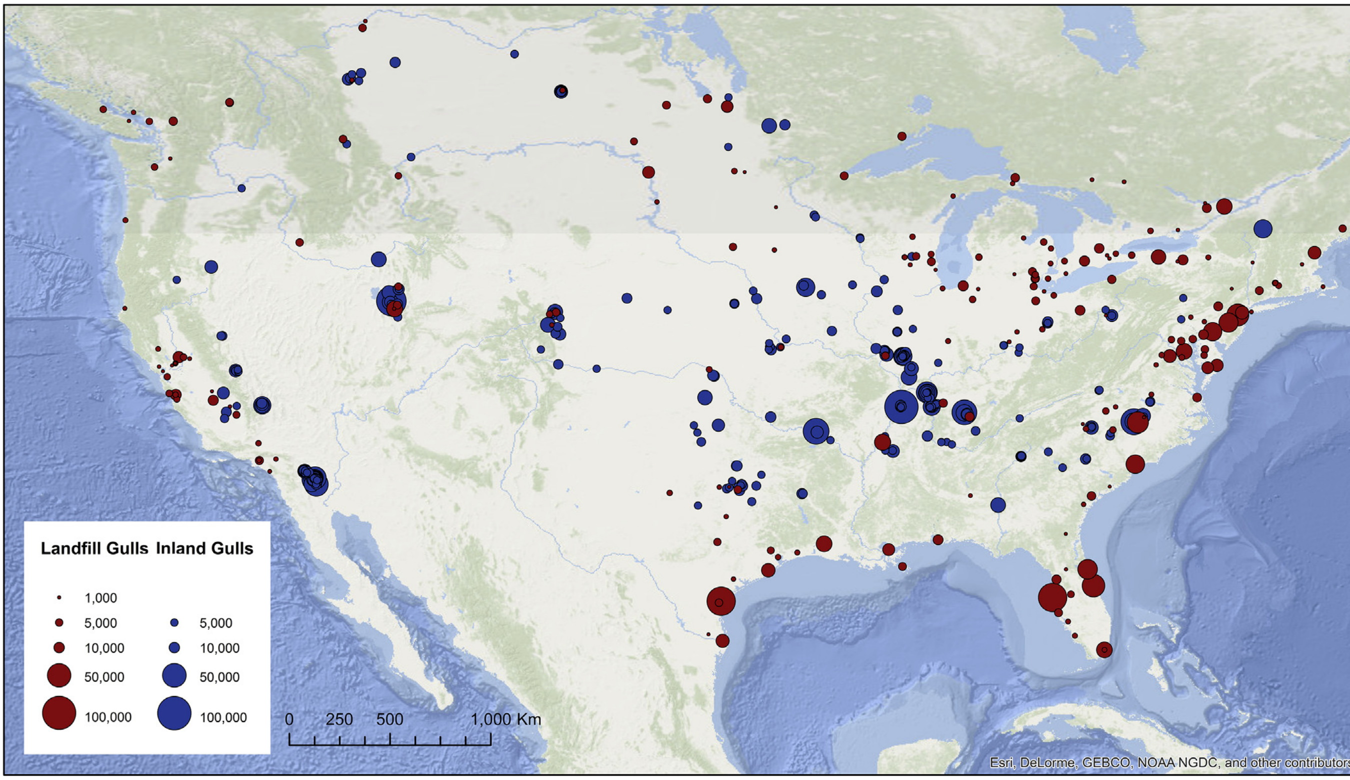

Fig. 2. Map of eBird data showing gull flocks of >1000 birds at "landfill" or "dump" hotspots (red) and of >5000 birds at hotspots >50 km from a marine, estuarine or Great Lakes coast lines (blue). Dot sizes are proportional to maximum number of gulls observed at each site. These data include counts of Herring Gull (*Larus argentatus*), Ring-billed Gull (*Larus delawarensis*), California Gull (*Larus californicus*), Great Black-backed Gull (*Larus marinus*), Glaucous-winged Gull (*Larus glaucescens*), Western Gull (*Larus occidentalis*), Laughing Gull (*Leucophaeus atricilla*), and Franklin's Gull (*Leucophaeus pipixcan*; landfill data only). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

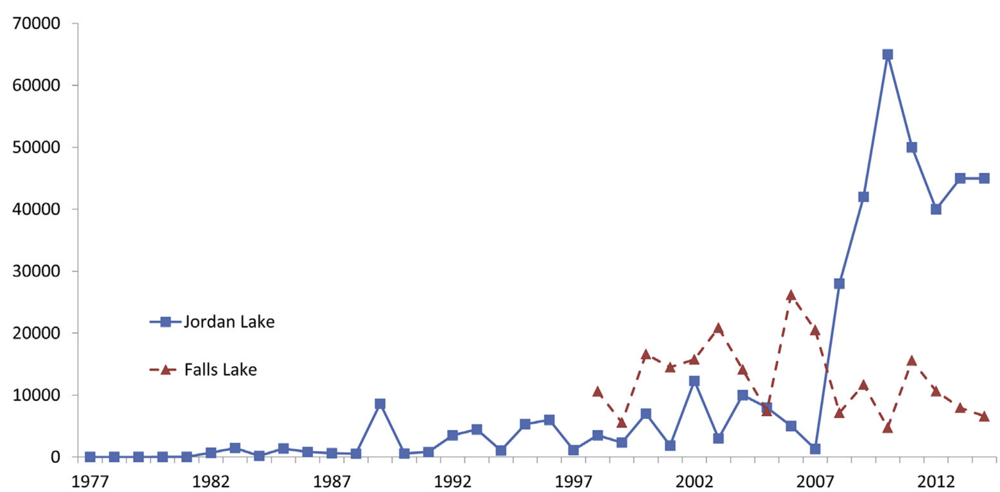

Fig. 3. Christmas Bird Count totals for Ring-billed Gull (*L. delawarensis*) at two reservoirs near Raleigh, North Carolina, USA. In 2008 the North Wake Landfill near Falls Lake closed and the South Wake Landfill near Jordan Lake opened.

present. For subsequent biogeochemical calculations we use the five-year mean flock size from 2010 to 2014 of 9000.

3.3. Fecal contents, loading and value

The nutrient contents of gull feces at the South Wake Landfill were highly variable (Fig. 4), but mean N and P are similar to other published values (Table 1). Feces were on average 33.6% C, 9.4% N and 1.5% P by weight. When we applied these values to a nutrient export model (Hahn et al., 2007), we found that the gull flock of 49,000 overwintering at the South Wake Landfill transports 6620 kg N and 1070 kg P into the New Hope arm of Jordan Lake. Gull loading represents 1.21% of New Hope N loading, and 2.07% of New Hope P loading. The TMDL reduction targets for combined Upper & Lower Watersheds (35% N and 5% P of Upper New Hope loading) are 157,000 kg N and 1983 kg P. Therefore gull nutrient

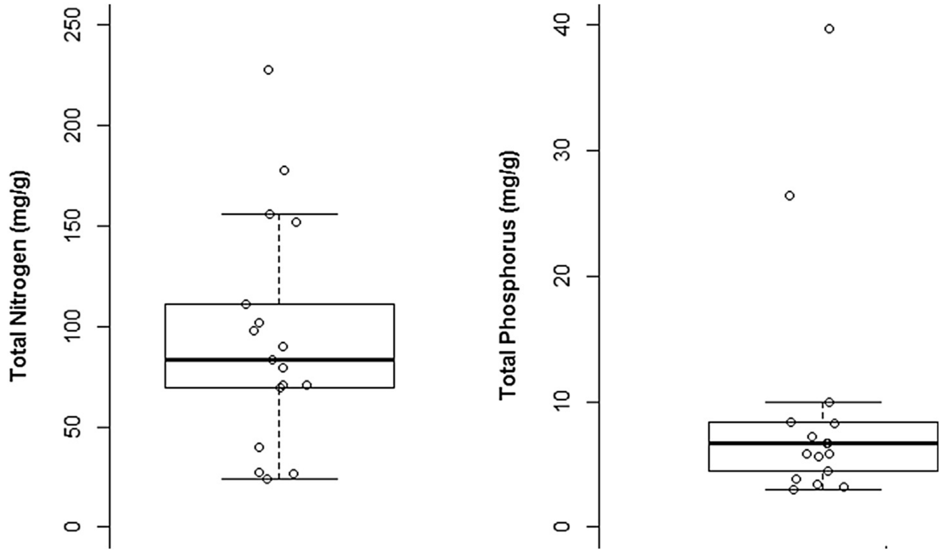

Fig. 4. Total nitrogen and total phosphorus content of Ring-billed Gull (*Larus delawarensis*) fecal droppings (n = 17) collected from the South Wake Landfill in North Carolina, USA. Highest phosphorus value (110.9 mg/g) not shown for clarity.

Table 1
Review of mean nitrogen and phosphorus content of gull feces.

Gull Species		Nitrogen	Phosphorus	Diet	Source
		(mg g^{-1})			
Black-headed	*Chroicocephalus ridibundus*	54.3	3.4	landfill	Gould and Fletcher 1978
Black-headed	*C. ridibundus*	72.4	78.6	natural mix	Gwiazda 1996
Black-tailed	*Larus crassirostris*	152.0		natural mix	Mizutani and Wada, 1988
Common	*L. canus*	70.3	4.2	landfill	Gould and Fletcher 1978
Herring	*L. argentatus*	103.9	6.6	landfill	Gould and Fletcher 1978
Herring	*L. argentatus*	12.5	15.3	natural mix	Portnoy 1990
Herring	*L. argentatus*	29.6	16.2	natural mix	Marion et al., 1994
Lesser Black-backed	*L. fuscus*	68.6	4.3	landfill	Gould and Fletcher 1978
Ring-billed Gull	***L. delawarensis***	**94.5**	**15.3**	**landfill**	**this study**
Mean		73.1	18.0		

inputs represent 4.2% of N and 54.0% of P reduction targets for the New Hope arm of Jordan Lake. In the Jordan Lake watershed the state-assessed values of N and P are currently $275 and $840 per kg, respectively (North Carolina Division of Environmental Quality; www.deq.nc.gov). Therefore, the gull feces transported from the South Wake Landfill to Jordan Lake has a nutrient offset value of $2,719,000 y^{-1}.

Gulls also consumed and diverted roughly 95 Mg of C from the landfill y^{-1}, assuming their food is 40% C by dry weight and that they feed at the landfill 120 days out of the year. The literature suggests that organic C buried in a landfill can theoretically be anaerobically converted to CH_4 at 33% efficiency (Bogner and Spokas, 1993), which would correspond to 32 Mg of potentially avoided CH_4 emissions y^{-1}. This magnitude of avoided CH_4 emissions is roughly equivalent to the 29 Mg of CH_4 that are captured daily as landfill gas to maintain the 6 MW power generation capacity the South Wake Landfill claims on its website (www.wakegov.com/recycling/division/swl/Pages/gas.aspx; accessed 21 November 2016).

Using the same models and assumptions described above (with mean gull mass for the seven gull species from Rodewald, 2015), we estimate that the 1.4 million gulls documented at landfills transport 39,000 kg of P and 240,000 kg of N y^{-1} to roosting sites and avoid roughly 1 Tg y^{-1} of landfill CH_4 emissions.

4. Discussion

4.1. How many gulls use landfills?

The eBird data we use has several limitations: 1) some landfills with large populations of gulls are not accessible to birders and will be left out of the database entirely; 2) methods for estimating/counting gull numbers are not standardized; 3) even diligent, experienced bird counters tend to underestimate flock size by 50–60% (Frederick et al., 2003; Chris Hill pers. comm.). These limitations each contribute omission errors, meaning that the 1.4 million gulls documented feeding on landfills is likely to be a severe underestimate.

We overlay the large flocks of inland gulls (Fig. 2) to capture the numbers and distribution of gulls that are likely using landfill food sources, but have not been documented at landfill-associated eBird hotspots. The inland gull data suffers from double-counting and other commission errors, such as gull flocks subsisting on natural inland food sources. Because of these commission errors, we do not analyze the inland gull data quantitatively.

Instead we start with the more conservative landfill gull data set of 1.4 million birds and estimate the magnitude of underestimates stemming from commission error sources to generate a more realistic estimate of the continent-wide landfill gull population. By scaling up by factors of 2.5 to correct for count underestimation and 1.6 (based on 8 of 21 landfills from the Facebook survey that were not present in the eBird data) we speculate that the number of gulls utilizing landfills in North America is probably greater than five million. Given the available data and underlying assumptions, this figure is imprecise, but probably a more accurate order-of-magnitude estimate for North American landfill gulls.

Data from Falls and Jordan Lakes in North Carolina provide strong anecdotal evidence for the affinity between gulls flocks and landfill food sources. The coincident closing of the North Wake Landfill and opening of the South Wake Landfill appears to have shifted tens of thousands of gulls from Falls Lake to Jordan Lake. At Falls Lake a population of roughly 9000 gulls does persist despite the elimination of the important food source of the North Wake Landfill. This population, though similar in absolute size to the one that existed decades ago while the North Wake Landfill was operating, represents less than one-fifth of the Falls-Jordan regional gull population, whereas it used to represent two-thirds. Therefore, while the absolute number of gulls at Falls Lake did not change dramatically, the shift is likely masked by an overall increase in the regional gull pool. Furthermore, the gulls that remain at Falls Lake appear to be utilizing the smaller Butner Landfill, 15 km to north of the roosting area of Falls Lake. The Butner Landfill is not included in any Christmas Bird Counts, nor is it accessible to recreational birders, so no count data are available for this site, but counters at Falls Lake have observed streams of gulls leaving the lake in the early morning on a flight vector oriented directly toward the landfill (Brian Bockhahn, pers. comm.). In addition to the Butner Landfill the Falls Lake gulls are able to utilize more dispersed anthropogenic food sources found scattered across the neighboring suburban areas of northern Wake, southern Granville and northern/eastern Durham counties. The region, known by the US Census Bureau as the Raleigh-Durham-Cary-Chapel Hill Combined Statistical Area, has experienced tremendous human population growth, with 2015 census estimates more than three times greater than the recorded population in 1990. Inevitably, the supply of anthropogenic gull food will have increased as a result.

4.2. Nutrient transport impacts

In the aggregate, we found that gulls at landfills cause a massive translocation of nutrients from landfills to roosting sites. Although this process could be considered beneficial if gulls were to roost on agricultural lands, the nutrients are primarily transported into water bodies, such as supply reservoirs and coastal estuaries, which is a concern. Our study flock at the South Wake Landfill/Jordan Lake appears to be contributing a significant nutrient input to an important water supply. We estimate that gulls load one-half of the total TMDL reduction target for P into the New Hope arm of Jordan Lake. Not only is the P transported by gulls relatively costly in the context of local monetary values of nutrient reduction, but it is also likely to be more harmful than P reaching the lake as runoff, much of which will be bound to sediments and relatively unavailable for rapid eutrophication. Although to our knowledge no studies have examined the bioavailability of P specifically in gull feces, numerous studies have shown that phosphorus in various types of manure is mostly bioavailable (Li et al., 2014; Nahm, 2003; Tiecher et al., 2014). In contrast, P bound to suspended sediment can vary widely but in general tends to have much lower bioavailability (Depinto et al., 1981; Dorich et al., 1984; Ekholm, 1994; Ellis and Stanford, 1988). Therefore the impact of gull feces on algal growth, chlorophyll content, turbidity and other such measures of eutrophication is likely to be much greater than is indicated simply by the total load of P. Given that landfill gull flocks are widespread throughout North America, we speculate that similar phenomena potentially occur in many other local contexts, with associated costs.

To improve water quality, whether at Jordan Lake or at other important gull roosts, regional managers could pursue a campaign to eliminate gull feeding at the South Wake Landfill. Gull control has been proven effective in numerous cases, though costs may be high (Belant, 1997; Clark et al., 2016; Soldatini et al., 2008). A site-specific cost-benefit analysis is beyond the scope of this paper, but assuming that an effective program could reduce the Jordan Lake wintering gull population from current levels to those comparable with Falls Lake (49,000 to 9,000, an 81% reduction), the potential value of avoided N and P loading would be more than $2.2 million. Gull control alone will not solve Jordan Lake's eutrophication problem, but it could potentially alleviate significant marginal costs that might otherwise need to be spent on wetland and stream mitigation banking (Nobles et al., 2014; Rao et al., 2012) or the cost of potentially taking agricultural land out of production, as the P loading alone from gulls in the Jordan Lake watershed is equivalent to the P export from approximately 2000 acres of corn or 11,000 acres of pasture (Harmel et al., 2006).

At the continental scale, the nutrient impacts of landfill gulls are massive: 1.4 to 5 million gulls are capable of transporting 39,000 to 139,000 kg of P and 240,000 to 858,000 kg of N y^{-1} to neighboring water bodies. Assuming most of these roosting water bodies are subject to TMDLs, the nutrient offset cost imposed by landfill gulls could easily be greater than $100 million.

It is worth mentioning that organic waste diverted from landfills by gulls may provide some CH_4 emissions avoidance. The fate of C consumed by gulls is aerobic respiration into carbon dioxide. In contrast the methanogenic fate of organic C buried in a landfill is theoretically as high as 33% (Bogner and Spokas, 1993). Although, recalcitrant organic forms such as lignin and cellulose are found to be reasonably well-preserved in excavated landfills, the organic food waste palatable to gulls is much more likely to be decomposed anaerobically and produce methane at C efficiencies much closer to laboratory rates. In practice, however, a large percentage of the CH_4 produced inside a landfill may be oxidized by methanotrophic bacteria in surficial sediments before it reaches the atmosphere and/or captured by natural gas recovery, as is practiced at the South Wake Landfill. Some landfills have been shown to be net CH_4 sinks because of the high efficiency of CH_4 oxidation (Bogner et al., 1995). So our estimate of avoided equivalent C emissions should be considered a theoretical maximum and not a practical figure for decision-making by managers. Furthermore, the potential value from a greenhouse gas/carbon credit perspective is relatively small based on our estimates of 1.1–3.9 Tg of potential CH_4 emission avoidance y^{-1}. This figure represents a small fraction of the 5920 Tg CH_4 emitted by United States landfills in 2014 (US Environmental Protection Agency, 2016).

4.3. Conservation implications

Since the nutrient consequences of gull presence at landfills we document in this study may inspire some local and regional planners to evaluate the reduction of gull populations, we should point out that none of the dominant species observed feeding at landfills are on any threatened species lists. On the contrary, Ring-billed, Herring and Laughing Gulls, have all increased dramatically since historic times, a trend attributed to their ability to utilize anthropogenic food sources (Belant et al., 1998, 1995; Burger, 1981; Kadlec and Drury, 1968). Managing landfills to reduce or eliminate gull feeding is best seen as ending an anthropogenic subsidy rather than as animal persecution, as gull control can be achieved using non-lethal methods.

5. Conclusions

We conclude that massive flocks of gulls are common and widespread at landfills and that their capacity to transport nutrients may be contributing to the eutrophication of aquatic ecosystems and water supplies. In the context of total maximum daily load nutrient reduction targets, gulls feeding at landfills are likely to be costly in the aggregate at continent scales and are certainly worthy of attention from local managers of the Jordan Lake watershed.

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