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SHOREBIRD RESPONSES TO CONSTRUCTION AND OPERATION OF A LANDFILL ON THE ARCTIC COASTAL PLAIN

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Abstract. Although much of the Arctic Coastal Plain has remained undeveloped, oil and gas industries, new and expanding villages, as well as tourism are likely to increase in the near future. One potential effect of increased human development is increased anthropogenic waste and the need to dispose of this waste in landfills. We investigated potential indirect effects of the North Slope Borough landfill on breeding shorebirds by examining changes in environmental conditions (predator densities and timing of snow melt) and measures of shorebird reproduction (nest-initiation dates, nest density, nest survival, and return rates) in relation to construction and deposition of waste in the landfill. This study included one year of pre-construction data (2004), three years when landfill roads and fences were being constructed (2005–2007), and five years when waste was being deposited (2008–2012). We monitored 364 shorebird nests within a 36-ha plot (approximately half of which was inside the landfill and half outside). Construction of a fence around the landfill reduced snow levels inside the landfill, leading to earlier snow melt and likely to shorebirds initiating nests earlier. Densities of avian predators increased following waste deposition, but nest densities, nest survival, and return rates were generally greater inside the landfill than outside in all years after landfill construction. Our results indicate that fences placed around landfills and procedures to reduce attraction of predators to landfills can minimize indirect negative effects of landfill construction and operation and even favor species breeding in the area.

Key words: Arctic, development, landfill, nest density, nest survival, predation, shorebird.

Respuestas de las Aves Playeras a la Construcción y Operación de un Relleno Sanitario en la Planicie Costera Ártica

Resumen. Aunque la mayoría de la Planicie Costera Ártica ha permanecido sin desarrollo, las industrias de petróleo y gas, los pueblos nuevos y en expansión, así como el turismo probablemente incrementarán en el futuro cercano. Un efecto potencial del incremento del desarrollo humano es el aumento de los desecho antropogénicos y la necesidad de disponer estos desechos en rellenos sanitarios. Investigamos los efectos potenciales indirectos del relleno North Slope Borough en la reproducción de las aves playeras mediante el examen de los cambios en las condiciones ambientales (densidad de depredadores y tiempo de derretimiento de la nieve) y de variables de la reproducción de las aves playeras (fecha de inicio del nido, densidad de nidos, supervivencia del nido y tasas de retorno) en relación con la construcción y el depósito de residuos en el relleno sanitario. Este estudio incluyó un año de datos previo a la construcción (2004), tres años mientras los caminos y los cercados del relleno estaban siendo construidos (2005–2007) y cinco años mientras se depositaban los residuos (2008–2012). Monitoreamos 364 nidos de aves playeras adentro de una parcela de 36 ha (aproximadamente la mitad de los cuales estaban adentro del relleno y la mitad afuera). La construcción del cerco perimetral del relleno redujo los niveles de nieve adentro del relleno, llevando a un derretimiento más temprano de la nieve y probablemente al inicio más temprano del nido de las aves playeras. Las densidades de depredadores de aves aumentó luego del depósito de residuos, pero las densidades de nidos, la supervivencia del nido y las tasas de retorno fueron generalmente mayores adentro del relleno que afuera en todos los años luego de la construcción del relleno. Nuestros resultados indican que los cercos perimetrales de los rellenos y los procedimientos para reducir la atracción de depredadores a los rellenos pueden minimizar los efectos negativos indirectos de la construcción y operación del relleno e incluso favorecer la reproducción de especies en el área.

INTRODUCTION

Increasing human populations and the continual expansion of development into rural areas have resulted in increased human–wildlife interactions, which may affect birds adversely. One such development is the construction of landfills. Landfill construction not only removes suitable habitat for many species, it may also alter habitat, increase disturbance, and provide food subsidies that favor predators. Previous studies investigating the effects of landfills have

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focused on the spatial and temporal distribution and behavior of birds foraging at landfills, especially as it relates to human–wildlife interactions (e.g., aircraft collision) and control of nuisance birds (Burger and Gochfeld 1983, Patton 1988, Belant et al. 1995, Gabrey 1997, Cook et al. 2008), as well as landfills' potential toxic effects on birds (Ortiz and Smith 1994). We are unaware of any studies that have investigated the potential effects of construction and operation of landfills on the birds breeding in or near the landfill, especially those that do not use the landfill as a food source.

Development within the Arctic Coastal Plain of Alaska is increasing, as oil and gas exploration continues to expand because of increased energy demands (National Research Council 2003). In addition, native villages are expanding or being created, tourism is increasing, and shipping ports are likely to be built as the Arctic Ocean becomes ice free (Ahlenius et al. 2005). Increased human waste from such developments has resulted in the construction of new landfills. Among the many birds for which the Arctic provides important habitat are millions of nesting and migrating shorebirds and waterfowl (Brown et al. 2007, Johnson et al. 2007, Bart et al. 2012). However, few studies have investigated how waste deposition is affecting these wildlife resources.

In this study, we assessed potential indirect effects (rather than direct habitat loss) of the construction and operation of the North Slope Borough (NSB) landfill near Barrow, Alaska, on the local bird community by examining how environmental conditions (predator density and snow melt) and measures of avian reproduction (nest phenology, nest density, nest survival, and adult return rates) varied (1) prior to construction (2004), during construction (2005–2007), and after construction (2008–2012) and (2) before and after waste deposition. We assessed these effects within remaining natural habitats within the landfill's boundaries. As shorebirds dominate the avifauna of the Barrow area and the surrounding arctic coastal plain in terms of both abundance and diversity (Johnson and Herter 1989, Johnson et al. 2007, Bart et al. 2012), we chose to focus on them in this study. Shorebirds not only allowed adequate sample sizes, they also likely serve as useful surrogates (Wiens et al. 2008) for assessing the potential effects of landfills on less numerous species, such as the threatened Steller's Eider (*Polysticta stelleri*), which breeds near Barrow (Quakenbush et al. 2004).

We predicted construction of the landfill would lead to shorebirds nesting inside the landfill initiating clutches earlier than those outside because the fence surrounding the landfill prevents snow from accumulating inside. We also predicted the number of predators, especially avian predators not deterred by the landfill fence, would increase after the landfill became operational and waste was deposited. However, we could not definitively predict how enhanced numbers of predators would affect survival of shorebird nests, as operation of the landfill could reduce or increase rates of predation on nesting shorebirds. For example, if alternative foods, such as raw organic waste, are available to predators, then predation pressure on shorebird nests, which are harder to find, may lessen. Conversely, predation pressure on shorebird nests may increase if predators are initially attracted to the landfill but organic wastes are incinerated or covered quickly. Not knowing how predators affect success of shorebird nests also made it impossible for us to predict how nest density and adult return rates would change with landfill construction and operation, as nest success is positively correlated with return rates (Gratto et al. 1985, Flynn et al. 1999) and apparent survival of adults (Hill 2012). To assess these predictions, we compared environmental conditions and measures of shorebird reproduction recorded simultaneously in and outside of the landfill through time.

METHODS

STUDY AREA AND LANDFILL OPERATION

Study area. In 2004, prior to construction of a new landfill near Barrow, we established a 36-ha study plot, of which approximately half was located outside and half inside the landfill's projected boundaries (Fig. 1). In addition, we established five similar plots away from the landfill. Although our procedures were the same on all plots, we report information from plots away from the landfill for comparative purposes only. We divided each plot into 144 quadrats marked by wooden stakes placed every 50 m to facilitate data collection. Habitat within the study plots consisted mainly of tundra dominated by sedges, grasses, and moss interspersed with small ponds, creating a mosaic of low, wet marsh habitat and higher, well-drained upland habitat (Brown et al. 1980). On the basis of a land-cover map developed by C. E. Tweedie et al. (unpubl. data), habitat types inside the landfill tended to be drier than those outside (59% vs. 47%). Drier habitats included dry-moist dwarf-shrub–graminoid tundra, dry dwarf-shrub–graminoid tundra, dry dwarf-shrub tundra, and bare ground. Wetter habitats included water, aquatic graminoid tundra, seasonally flooded graminoid tundra, wet graminoid tundra, and moist graminoid tundra.

Fox removal. To increase productivity of Steller's Eider, in 2005, the Endangered Species Office of the U.S. Fish and Wildlife Service (USFWS) began controlling arctic foxes (*Vulpes lagopus*) over ~220 km^2 (the "Eider Conservation Planning Area") including the greater Barrow area and the landfill (Fig. 1). Foxes were removed annually from mid-May through July, when they establish breeding territories and are relatively stable in number (Bair et al. 2011). Each year, trappers removed adults and kits at dens and opportunistically shot and trapped adults. From 2005 to 2012, 12–41 adult and 0–40 juvenile arctic foxes were removed annually within the Eider Conservation Planning Area (Gilsdorf and Rossi 2008, Savory et al. 2009, 2010, Bair et al. 2011; D. Safine, pers. comm.; Fig. 2). Year-to-year differences in the number of foxes removed likely reflected changes in fox

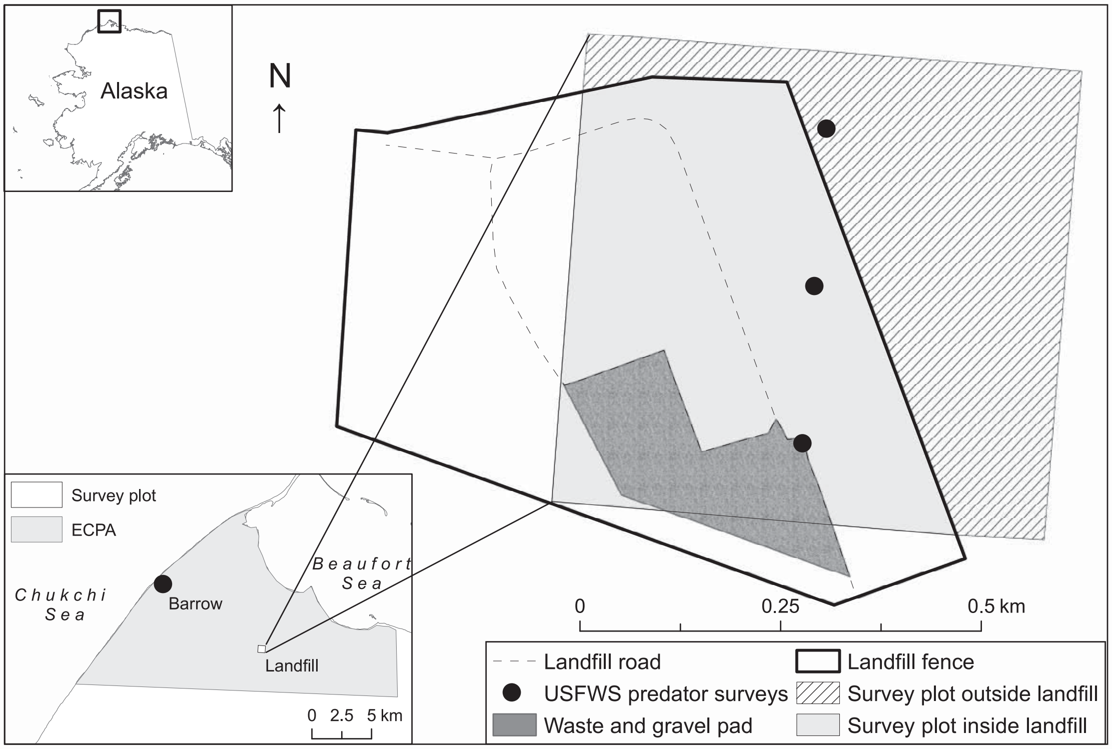

FIGURE 1. Location of shorebird study plot, U.S. Fish and Wildlife Service (USFWS) predator point count surveys, and the Eider Conservation Planning Area (ECPA) in relation to the North Slope Borough landfill near Barrow, Alaska, 2004–2012. Waste has only been deposited in the southwest section of the study plot; natural vegetation remains in other areas.

density or trapping methods (C. Rossi and T. Smith, pers. comm.). Particularly prominent was a change in trapping methods and a decrease in trapping effort in 2009 due to a high number of Snowy Owls (*Bubo scandiacus*) caught as by-catch in 2008.

Landfill construction and operation. During the winter of 2004, a fox-proof fence (buried below the surface and ~2.5 m tall) was erected surrounding the future landfill site, and access roads for bringing waste into the landfill were constructed (Fig. 2D). These roads were supplemented with gravel and compacted over the next two years. Non-combustibles and ash were initially brought to the landfill in the fall of 2007 (after shorebird studies were concluded for that year) and continued to be deposited daily until the fall of 2009, when an explosion at the site of the thermal oxidation system required disposal of unburned combustible wastes, including human food and other raw organic matter, in the landfill. The thermal oxidation system was repaired in the summer of 2010, although raw organic waste continues to be deposited to the present day (S. Barr and T. Mueller, pers. comm.). In a design called a "freezeback" landfill, an intermediate cover of gravel is placed over the waste from the previous year at the end of each summer to allow efficient cooling back to permafrost temperatures. When combustible waste was delivered to the landfill, it was slated to be covered on a daily basis to deter scavengers. However, covering of organic waste was dependent on access to gravel, which has been in short supply during some periods (Fig. 2). Currently, deposited waste has been restricted to the southwest portion of the landfill, with the remaining areas consisting of natural vegetation (Fig. 1).

ENVIRONMENTAL DATA

USFWS predator surveys. From 2004 to 2012, we conducted weekly to biweekly 10-min point counts of predators at three locations within the survey plot (Fig. 1) from early June to late July. The points were 200 m apart and ≥100 m from the plot's edge. Because predators, especially avian predators, were not restricted to either inside or outside the landfill, we considered predator counts a measure of predation pressure for the entire study plot, both inside and outside the landfill. During point counts, we noted all predators of shorebird nests within 300 m of each point, then used the total number of predators observed at all three points to represent predator abundance for a given survey date. Effort was made to avoid double counting individuals.

NSB predator surveys. The biological opinion associated with permitting of the landfill (U.S. Fish and Wildlife Service 2003) stipulated that predators—Glaucous Gulls (*Larus hyperboreus*), Common Ravens (*Corvus corax*),

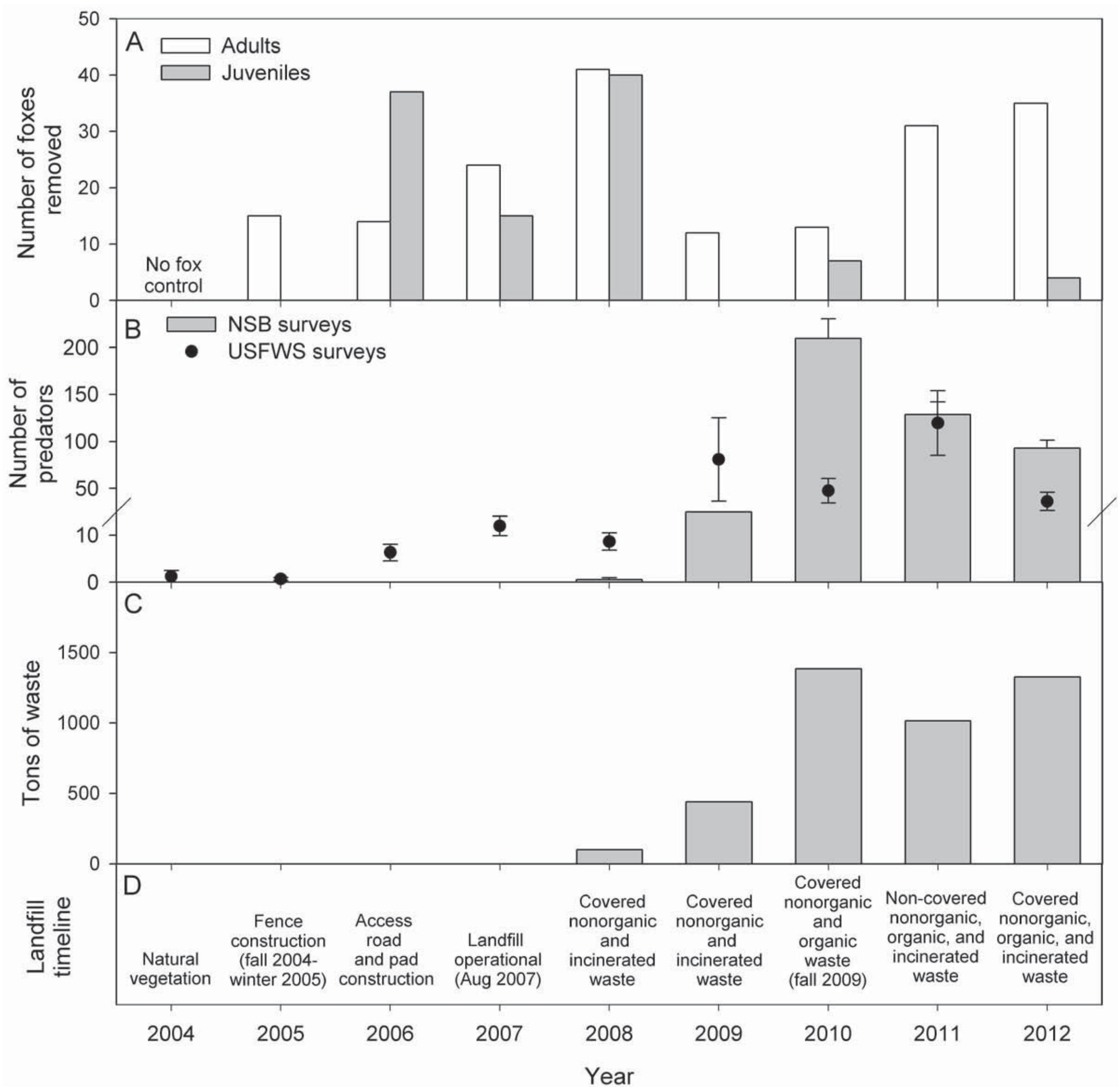

FIGURE 2. (A) number of foxes removed within the Eider Conservation Planning Area (see Fig. 1) and (B) mean number of avian predators observed within the North Slope Borough (NSB) landfill during U.S. Fish and Wildlife Service (USFWS) and NSB surveys conducted between 12 June–13 July (NSB surveys only conducted from 2007–2012) in relation to (C) amount of waste entering the NSB landfill during June and July and (D) timeline of NSB landfill construction and waste deposition near Barrow, Alaska, USA, 2004–2012.

and arctic foxes—be counted on days waste was delivered to the landfill beginning in 2007. We provided these data as an alternative measure of predator densities during landfill operation. Counts consisted of scanning the entire landfill, typically from the gravel pad where waste was being off-loaded, and tallying all predators observed when waste was delivered.

Snow surveys. From 2005 to 2012, we estimated the percentage of snow cover within 36 quadrats of 50 × 50 m inside the study plot to the nearest 5% every 2 to 5 days until ≤10% snow cover remained. We did not record snow cover in 2004, as most of the snow was gone by the time survey stakes were placed to mark the location of the plot. Because snow accumulated in a large drift along the windward (north and east) sides of the landfill fence (Fig. 1), we excluded eight quadrats near the fence from analysis because including them would have biased dates of snow melt later (especially outside the landfill). Additionally, we excluded four quadrats that fell within the active landfill area where waste was being deposited. We used the mean snow cover from the remaining 24 quadrats (12 inside and 12 outside the landfill) to estimate percent snow cover in and outside the landfill on a given survey.

SHOREBIRD DATA

Nest surveys. From 2004 to 2012, we located nests by single-person area searches, two-person rope drags, and opportunistically (Troy 1996, Naves et al. 2008). During area searches, surveyors searched plots systematically and found nests primarily by following individual birds displaying nest-attendance behaviors or, occasionally, by flushing an incubating bird. Area searches took place 4 hr per day, 6 days per week, from early June to early July each year. Near the end of June, we dragged a 35-m rope over the entire plot to flush incubating birds from nests.

Once a nest was found, we recorded the location with a hand-held GPS unit and determined the status of the nest as either eggs being laid or eggs being incubated. We visited nests found with less than four eggs (the modal clutch size for all species) daily until clutches were completed or until clutch size remained unchanged for two consecutive days. If clutch size remained unchanged from the day the nest was discovered or if a nest was discovered with four eggs, we floated eggs to determine their stage of incubation. We estimated clutch-initiation dates (i.e., date first egg laid) (1) from the date of laying, assuming one egg laid per day if the nest was found during laying, (2) by subtracting a species' incubation period (from the *Birds of North America* accounts; Poole 2005) from the date of hatching if the nest was found during incubation and the eggs hatched, or (3) from the embryo's age estimated by egg flotation (Liebezeit et al. 2007) if the nest was found during incubation but ultimately unsuccessful.

Evidence of hatching and failure was based on criteria developed by the Arctic Shorebird Demographics Network (Gates et al. 2012). Briefly, we checked nests every 3 to 5 days until 3 or 4 days prior to the estimated hatch date, after which we checked nests every 2 days until the eggs were starred and daily thereafter. We defined a nest as successful when at least one egg hatched (Mayfield 1975). Evidence of hatching included chicks seen in or near the nest (<50 m from nest within 2 days of hatching), marked adult(s) acting defensive or "broody," or egg shell fragments indicating hatching, the latter including shell fragments of 1–5 mm found in nest or the top or bottom of an eggshell located <5 m from nest within 4 days of the estimated hatch date (Mabee 1997). We considered a nest failed when (1) eggs were absent at least 4 days from estimated hatch date, (2) there were signs of predation (shell fragments in or near nest not indicating hatching [see above] and/or predator sign near nest), (3) there were signs of trampling (i.e., crushed eggs in nest and footprints near or on nest), (4) destroyed by weather (i.e., nest flooded, covered in snow), or (5) eggs were abandoned (i.e., eggs present more than 7 days after estimated hatch date or when eggs were cold and parents did not adjust a repositioned egg within 24 hr). If nest fate did not match these definitions or evidence was contradictory, we classified the fate as unknown (Manolis et al. 2000).

Capture and handling. From 2004 to 2012, we captured adult shorebirds on nests with a modified luchock trap (or bownet; Priklonsky 1960) and marked them with a U.S. Geological Survey metal leg band, a unique combination of colored leg bands, and a single dark green flag with ends soldered to reduce band loss. Return rates were based on physical captures of birds on nests and resightings of birds near nests. If an individual was not recaptured on a nest, we retained resightings only if they could be definitively assigned to a marked nest (e.g., flushed from nest, observed returning to incubate nest).

STATISTICAL ANALYSES

For all analyses, we restricted the data to 2005–2012, as we were interested in investigating how the presence of the landfill affected environmental conditions and measures of shorebird reproduction. We also present data from 2004, the year prior to landfill construction, for comparison, but did no statistical analyses to evaluate changes before and after landfill construction. For the 2004 data, we partitioned nests as in or outside of the landfill by the location of the future fence. In some cases, we also compared measures of shorebird reproduction in years without (2005–2007) and with (2008–2012) waste deposition into the landfill. Unless noted otherwise, we used SAS (SAS Institute 2008) for all statistical analyses and report means ± SE.

Predator trends. To characterize changes in predator numbers in relation to waste deposition, we estimated the mean number of predators observed during both USFWS and NSB surveys for a given year. For both surveys, we used data only from 12 June to 13 July, when 95% of all shorebird nests were active. For USFWS surveys, we compared mean predator counts in years with and without waste deposition by a *t*-test. We did not do this analysis for NSB surveys, as only one year of data was available prior to waste deposition in the landfill.

Timing of snow melt. We used the mean percent of snow cover estimated during the first survey period (i.e., 3–5 June) to represent the timing of snow melt for each year, as the coverage of snow inside the landfill was already <50% by this date. We used a *t*-test, paired by year, to test for differences in timing of snow melt between areas in and outside the landfill.

Nest-initiation dates. To characterize changes in nest-initiation dates in relation to the landfill, we estimated mean nest-initiation dates for the most abundant species, the Semipalmated Sandpiper (*Calidris pusilla*), Pectoral Sandpiper (*C. melanotos*), Dunlin (*C. alpina*), and Red Phalarope (*Phalaropus fulicarius*), both in and outside the landfill each year. As snow accumulated along and near the windward side of the landfill fence, potentially biasing nest-initiation dates later (especially outside the landfill), we excluded from analysis all nests placed within 20 m of the outside of the fence and 10 m of the inside of the fence. For each species, we used a *t*-test, paired by year, to test for differences in mean nest-initiation dates between areas in and outside the landfill.

Nest density. We calculated the density of nests of all species combined, as well as for the most abundant species (Semipalmated Sandpiper, Pectoral Sandpiper, Dunlin, and Red Phalarope) both in and outside the landfill each year as a standard proportion of the area of the study plot in or outside the landfill, respectively. After construction of the pad and deposition of waste, habitat available for nest placement inside the fence was reduced. Therefore, from 2005 to 2012, we excluded the area in which waste was deposited from nest-density calculations. For each species and for all species combined, we used a *t*-test, paired by year, to test for differences in nest density between areas in and outside the landfill. Additionally, for each species and for all species combined, we used a *t*-test to test for differences in nest density between years with and without waste deposition; we conducted this analysis separately for nests located in and outside the landfill.

Nest survival. For descriptive purposes, we calculated apparent nest survival of all species in and outside the landfill each year as the number of successful nests divided by the total number of nests. We excluded from these calculations nests with unknown fates or nests destroyed by researchers. In addition, we estimated daily survival rates for nests of all species in and outside the landfill each year with program Mark (White and Burnham 1999). For the 17 nests with unknown fates, we used data up to the visit prior to finding the nest empty, as the nest was successful until this point. Similarly, we used the data up to the last visit for three nests that were either accidentally stepped on or collected for other studies.

To understand how the landfill may have affected nest survival, we investigated a suite of nest-survival models with program Mark (Dinsmore et al. 2002). We considered 84 a priori candidate models consisting of biologically relevant combinations of uncorrelated variables, including (1) season, measured as a linear and quadratic trend in days since the beginning of the nesting season (Dinsmore et al. 2002, Cooch and White 2012); (2) year, measured as a categorical effect and as a linear and quadratic trend; (3) landfill, measured as a categorical effect of in or outside landfill (coded 0 and 1, respectively); (4) landfill operation, measured as a categorical effect of years with or without waste deposition (coded 1 and 0, respectively); and (5) incubation behavior, measured as a categorical effect of species with biparental or uniparental incubation (coded 0 and 1, respectively). We used Akaike's information criterion corrected for small sample size (AIC_c) to rank models and considered a model plausible when $\Delta AIC_c < 2$ (Burnham and Anderson 2002). We calculated AIC_c weights for all models and determined likelihoods of parameters by model averaging (i.e., sum of weights for models including a given parameter; Burnham and Anderson 2004). We present parameter estimates, standard errors, and 95% confidence intervals from the top-ranked models. In four instances, nests were found the day of hatching. Because the number of exposure days in these instances was zero, we did not include these nests in program Mark's nest-survival models, although we included them in estimates of apparent nest survival.

Return rates. For site-faithful species (Semipalmated Sandpiper and Dunlin; Pitelka et al. 1974), we determined return rates for adults in and outside the landfill each year with a standard proportion (i.e., number of marked adults nesting in the same location in two consecutive years divided by total number of marked adults nesting in this location in the first year). For each species, we used a chi-squared analysis with Yates' correction for continuity to test for independence in adult return rates between individuals nesting in and outside the landfill. For this analysis, we combined information across years because of low sample sizes.

We determined the proportion of adults that changed nesting locations (i.e., in to outside the landfill or vice versa) in consecutive years by dividing the number of marked adults nesting in a different location in the second year by the total number of marked adults nesting in the first location in the first year. For each species, we used a chi-squared analysis with Yates' correction for continuity to test for independence in the rate of change of nest location between individuals nesting in and outside the landfill. For this analysis, we combined information across years because of low sample sizes. In analyses of return rates, an individual may have been used more than once if it was resighted in more than one year, but 76% of individuals that returned were resighted for only one or two years.

RESULTS

PREDATOR TRENDS

As predicted, both USFWS and NSB surveys indicated that predators on shorebird nests increased in number after waste began entering the landfill in August 2007 (USFWS: 6.3 ± 3.3 predators without waste and 58.5 ± 19.2 predators with waste; NSB: 0 predators without waste and 89.7 ± 38.2 predators with waste), but in the USFWS surveys the difference was not significant ($t_6 = -2.03$, $P = 0.09$; Fig. 2). This was likely due to a one-year time lag in predator response, with predator numbers increasing in 2009 and remaining high thereafter (Fig. 2). In fact, the mean number of predators detected was an order of magnitude greater from 2009 to 2012 (71.0 ± 18.8) than from 2005 to 2008 (6.9 ± 2.4; $t_6 = -3.38$, $P = 0.01$; Fig. 2). The increases in predators following waste deposition into the landfill was due mainly to a large increase in the Glaucous Gull, which made up >99% of all predators detected after 2007. Few other avian predators—2 Snowy Owls, 4 Long-tailed Jaegers (*Stercorarius longicaudus*), 6 Parasitic Jaegers (*S. parasiticus*), 30 Pomarine Jaegers (*S. pomarinus*), 3 unidentified jaegers, and 9 Common Ravens—and no mammalian predators were detected during either USFWS or NSB surveys after 2007.

Landfill operations may have influenced predator densities, as NSB surveyors observed fewer predators in 2008 and 2009, when only residual ash from incinerated waste was deposited in the landfill and the waste was covered regularly (Fig. 2). Additionally, the greatest numbers of gulls were observed by NSB surveyors in 2010 and 2011, when only raw organic waste was deposited or gravel was not placed over waste regularly. However, counts by USFWS surveyors were similar from 2009 through 2012 and did not reflect changes in the type of waste being deposited or whether waste was being regularly covered with gravel.

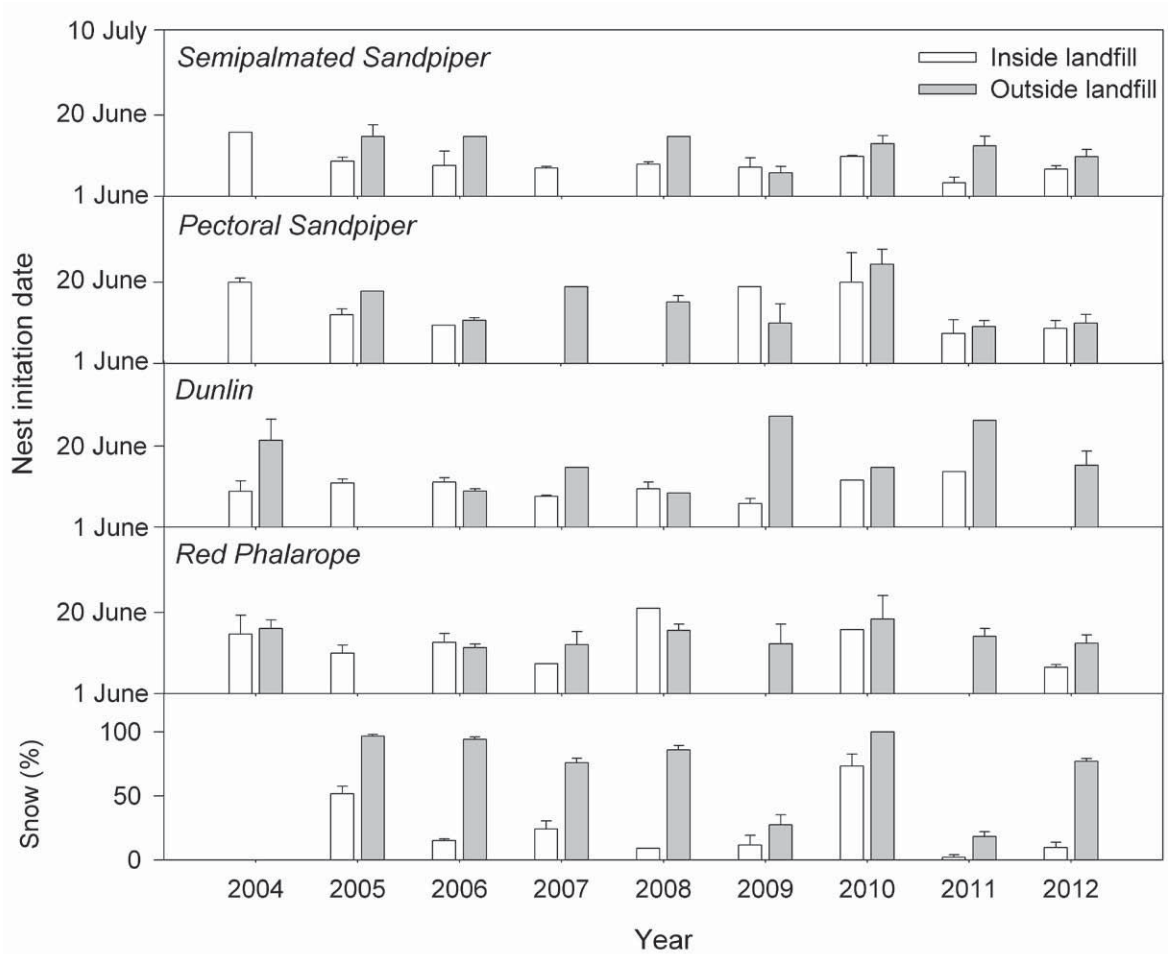

FIGURE 3. Mean shorebird nest initiation dates in relation to mean percent snow cover in and outside the North Slope Borough landfill near Barrow, Alaska, USA, 2004–2012. No snow surveys were conducted in 2004 and snow cover limited to levels on 3–5 June in other years. Nest initiation dates in 2004 provide a baseline estimate prior to landfill construction (see Figure 2, panel D).

TIMING OF SNOW MELT

As predicted, from 2005 to 2012, mean percent snow cover during the first survey period (3–5 June) was significantly lower inside (24.6 ± 8.8%) than outside (71.9 ± 11.2%) the landfill (paired *t*-test: $t_7 = -5.17$, $P = 0.001$; Fig. 3).

NEST-INITIATION DATES

From 2004 to 2012, we located 364 shorebird nests (24, 32, 40, 21, 37, 41, 31, 56, and 82 in successive years), representing 11 species. This included 9 of the American Golden-Plover (*Pluvialis dominica*), 1 of the Ruddy Turnstone (*Arenaria interpres*), 103 of the Semipalmated Sandpiper, 7 of the Western Sandpiper (*Calidris mauri*), 8 of the Baird's Sandpiper (*C. bairdii*), 81 of the Pectoral Sandpiper, 48 of the Dunlin, 5 of the Buff-breasted Sandpiper (*C. subruficollis*), 6 of the Long-billed Dowitcher (*Limnodromus scolopaceus*), 20 of the Red-necked Phalarope (*Phalaropus lobatus*), 75 of the Red Phalarope, and 1 of unknown species. When only the most abundant species (Semipalmated Sandpiper, Pectoral Sandpiper, Dunlin, and Red Phalarope) are considered, dates of initiation of five nests were unknown, and 13 nests were excluded because they were located in the snow drift area ($n = 289$).

In 2004, nest-initiation dates for all species were within the range of dates observed after construction of the landfill fence (Fig. 3). Low sample sizes in 2004 allowed comparisons of nest-initiation dates between in and outside of the landfill for only two species; Dunlins tended to initiate nests earlier inside the future landfill fence than outside, but initiation dates for the Red Phalarope were similar (Fig. 3). From 2005 to 2012, however, nest-initiation dates for all species were always earlier inside the landfill than outside (Semipalmated Sandpiper: 8 June ± 0.6 days vs. 13 June ± 1.2; Pectoral Sandpiper: 13 June ± 2.1 days vs. 15 June ± 1.9; Dunlin: 11 June ± 0.9 days vs. 17 June ± 2.7; Red Phalarope: 11 June ± 2.6 days vs. 14 June ± 0.9). However, these differences were significant only for the Semipalmated Sandpiper (paired *t*-test: $t_6 = -3.67$, $P = 0.01$; Fig. 3).

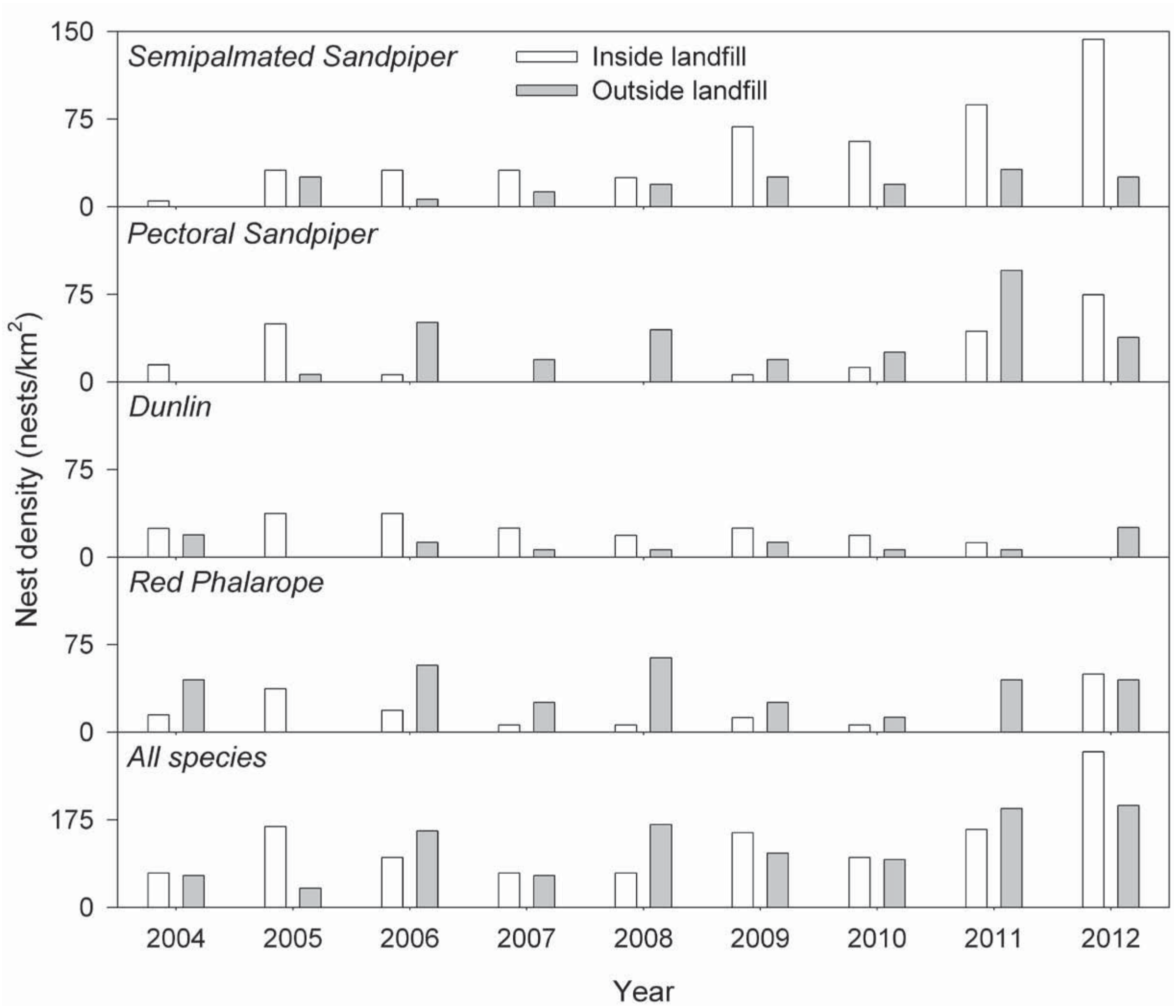

FIGURE 4. Shorebird nest density in and outside the North Slope Borough landfill near Barrow, Alaska, USA, 2004–2012. Nest density in 2004 provides a baseline estimate prior to landfill construction (see Figure 2, panel D).

NEST DENSITY

In 2004, prior to landfill fence construction and fox control, nest densities for all species were within the range observed after construction, but for most species, densities inside the future landfill were greater than those outside (Fig. 4). After the landfill fence was constructed (2005–2012), nest densities remained greater in the landfill for the Semipalmated Sandpiper (inside: 59.1 ± 14.3 nests km^{-2}, outside: 20.7 ± 2.9 nests km^{-2}), Dunlin (inside: 21.8 ± 4.4 nests km^{-2}, outside: 9.5 ± 2.7 nests km^{-2}), and all species combined (inside: 139.1 ± 27.9 nests km^{-2}, outside: 128.1 ± 21.6 nests km^{-2}), but the difference was significant for the Semipalmated Sandpiper only (paired *t*-test: $t_7 = 2.98$, $P = 0.02$; Fig. 4). Conversely, the densities of Pectoral Sandpiper (inside: 24.1 ± 9.9 nests km^{-2}, outside: 37.4 ± 9.8 nests km^{-2}) and Red Phalarope nests (inside: 17.1 ± 6.2 nests km^{-2}, outside: 34.2 ± 7.8 nests km^{-2}) were greater outside the landfill than inside, but differences were not significant ($P > 0.05$; Fig. 4).

After deposition of waste in the landfill began, nest densities within the landfill declined for both the Dunlin (before: 33.2 ± 4.1 nests km^{-2}, after: 14.9 ± 4.2 nests km^{-2}) and Red Phalarope (before: 20.7 ± 9.0 nests km^{-2}, after: 14.9 ± 8.9 nests km^{-2}), although the difference was significant only for the Dunlin ($t_6 = 2.86$, $P = 0.03$; Fig. 4). Conversely, densities of nests of these two species outside the landfill increased following waste deposition, as well as in and outside the landfill for all species combined, the Semipalmated Sandpiper, and the Pectoral Sandpiper, but the amounts of increases were not significant ($P > 0.05$; Fig. 4).

NEST SURVIVAL

In 2004, prior to construction of the landfill fence and fox control, apparent survival of nests located outside the future landfill was generally greater than that of those located inside the future landfill, although confidence intervals overlapped (Fig. 5). Beginning in 2005, after fox control and fence

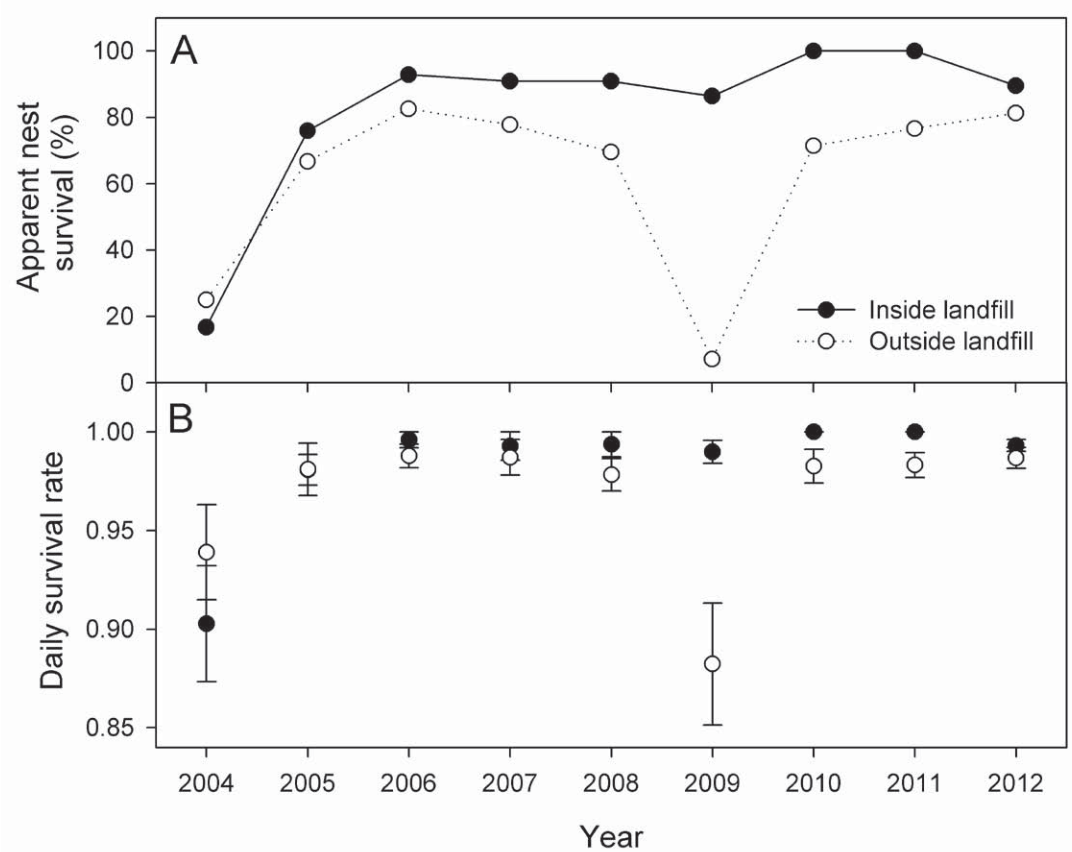

FIGURE 5. (A) apparent nest survival and (B) daily nest survival estimates from program Mark for shorebirds nesting in and outside the North Slope Borough landfill near Barrow, Alaska, 2004–2012. Nest survival estimates in 2004 provide a baseline estimate prior to landfill construction (see Figure 2, panel D).

construction, apparent nest-survival rates inside and outside the landfill increased. Nest survival remained high in the remaining years both in and out of the landfill, except in 2009 when virtually all nests outside the landfill failed. In all years, apparent nest survival was greater inside the landfill than outside (Fig. 5). As predicted, nest-survival rates varied with landfill practices, being greater in 2010 and 2011 when only raw organic waste was deposited or gravel was not placed over waste regularly (Fig. 5).

Using survival data from 339 nests found from 2005 to 2012, we estimated daily survival rates over a 57-day nesting season from 2 June to 28 July (i.e., day first nest discovered to day last nest hatched or failed). Among the 84 a priori nest-survival models evaluated, we consider three plausible (i.e., $\Delta AIC_c < 2$; Table 1). Within all plausible models, the interaction effect of landfill and year and either a linear or quadratic seasonal trend were included. In the top-ranked model (on which we base our parameter estimates), daily nest-survival rates varied by year, with survival of nests located inside the landfill generally being greater than that of nests located outside (Fig. 5). On the basis of whether confidence intervals surrounding the β coefficient overlapped zero, however, these differences were significant only for 2009, 2010, and 2011 (Table 2). Furthermore, daily survival rates decreased ($\beta = -0.071$) through the nesting season (i.e., linear time trend; Table 2). Including covariates for incubation behavior (second-ranked model) and the quadratic term for the season effect (third-ranked model) did not improve the fit of the top-ranked model. Parameter likelihoods indicated that the interaction between year and landfill (likelihood = 0.79) and the linear seasonal trend (likelihood = 0.72) were the most important variables in the top-ranked models, while incubation behavior (likelihood = 0.28) and the quadratic seasonal trend (likelihood = 0.28) were less important. Additionally, 95% confidence intervals for both of the latter parameters overlapped zero, suggesting these parameters were uninformative and insignificant for explaining variation in survival of shorebird nests.

RETURN RATES

From 2004 to 2011, we captured 85 Semipalmated Sandpipers and 37 Dunlins on nests in and outside of the landfill (Table 3). Of these, 32 Semipalmated Sandpipers and 14 Dunlins were recaptured or resighted in one or more years later. From 2005 to 2012, a greater proportion of both Semipalmated Sandpipers and Dunlins returned to nest inside than outside the landfill (Semipalmated Sandpiper: inside = 42%, outside = 15%;

TABLE 1. Top-ranked models (i.e., $w_i > 0.01$) from a set of 84 candidate models describing daily survival rates of shorebird nests in and outside the North Slope Borough landfill near Barrow, Alaska, USA, 2005–2012.

Model[a]	K	ΔAIC_c[b]	w_i[c]
S (landfill × year + linear seasonal trend)	17	0.00	0.41
S (landfill × year + linear seasonal trend + inc. behavior)	18	1.92	0.16
S (landfill × year + quadratic seasonal trend)	18	1.96	0.15
S (landfill + year + linear seasonal trend)	10	2.64	0.11
S (landfill × year + quadratic seasonal trend + inc. behavior)	19	3.86	0.06
S (landfill + year + quadratic seasonal trend)	11	4.37	0.05
S (landfill + year + linear seasonal trend + inc. behavior)	11	4.65	0.04

[a]Variables include year, landfill (i.e., inside or outside the landfill fence), linear or quadratic seasonal trend (i.e., linear or quadratic relationship between daily survival and days since the beginning of the nesting season), and incubation behavior (i.e., biparental or uniparental).
[b]Difference between model's Akaike's information criterion corrected for small sample size and the lowest AIC_c value. Intercept model $\Delta AIC_c = 45.96$.
[c]AIC_c relative weight attributed to model.

TABLE 2. Maximum-likelihood (logit-link) estimates from top-ranked model of rates of daily survival of shorebird nests in and outside the North Slope Borough landfill near Barrow, Alaska, 2005–2012.

			95% CI	
Parameter	Estimate	SE	Lower	Upper
2005	5.820	0.644	4.558	7.082
2006	7.417	1.116	5.230	9.604
2007	6.611	1.095	4.465	8.758
2008	7.241	1.166	4.955	9.527
2009	6.458	0.770	4.950	7.967
2010	25.453	0.000	25.453	25.453
2011	22.140	0.000	22.140	22.140
2012	6.673	0.641	5.417	7.929
Landfill (2005)	0.218	0.828	–1.405	1.841
Landfill (2006)	–1.134	1.122	–3.333	1.065
Landfill (2007)	–0.130	1.238	–2.557	2.297
Landfill (2008)	–1.377	1.077	–3.487	0.734
Landfill (2009)	–2.739	0.660	–4.032	–1.445
Landfill (2010)	–18.892	0.000	–18.892	–18.892
Landfill (2011)	–16.097	0.000	–16.097	–16.097
Landfill (2012)	–0.323	0.614	–1.527	0.882
Linear seasonal trend	–0.071	0.018	–0.106	–0.037

Dunlin: inside = 37%, outside = 9%; Table 3). The difference was significant, however, for the Semipalmated Sandpiper only (Yates corrected chi-squared: $\chi^2_1 = 6.56$, $P = 0.01$). From 2005 to 2012, the proportion of Semipalmated Sandpipers and Dunlins nesting outside that moved into the landfill to nest in a following year was greater than the proportion that moved out of the landfill (Semipalmated Sandpiper: out to in = 6%, in to out = 1%; Dunlin: out to in = 18%, in to out = 0%; Table 3); however, this difference was significant for only for the Dunlin (Yates-corrected chi-squared: $\chi^2_1 = 4.13$, $P = 0.04$).

DISCUSSION

We found that the construction and operation of the NSB landfill affected environmental conditions, and in turn, measures of shorebird reproduction as predicted. Snow accumulation on the windward side of the fence surrounding the landfill decreased snow levels inside the landfill, which in turn appeared to result in shorebirds nesting earlier (although the difference was significant for the Semipalmated Sandpiper only). This finding supports prior work that suggested snow melt is an important determinant of dates of initiation of shorebird nests, with birds nesting earlier if conditions allow (Smith et al. 2010). It should be noted, however, that differences in timing of snow melt may have been at least partially influenced by habitat type, with snow melting earlier in drier, higher areas inside the landfill than in lower, wetter areas outside the landfill. However, we found that in comparison to five other shorebird-study plots in Barrow, the percent snow cover from 3 to 5 June was significantly lower inside the landfill than at all other plots, regardless of habitat type (25% inside landfill versus 56–91% in other plots; RBL, unpubl. data). Similarly, differences in timing of nest initiation between inside and outside the landfill may also be confounded by habitat, especially if individuals nest first in the drier habitats found inside the landfill. However, using data from all six shorebird plots, we found that the earliest nests were almost always inside the landfill (e.g., 80% of all nests initiated prior to 1 June were found inside the landfill; RBL, unpubl. data). Therefore, we believe that earlier snow melt within the landfill can be attributed primarily to the fence blocking snow and that this earlier melt does in fact afford shorebirds an opportunity for earlier nesting.

We also found that avian predators (i.e., Glaucous Gulls) in or near the NSB landfill increased, but only after waste began entering the landfill (with a one-year lag) and not during construction (Fig. 2). Despite these greater numbers, nest-survival rates were generally high both in and outside the landfill throughout our study. Perhaps this should not have been surprising because other studies in the Arctic have found Glaucous Gulls to have little effect on survival of shorebird nests (Smith et al. 2007, Liebezeit and Zack 2008). The small effect Glaucous Gulls have on nests was also apparent in a study of the species' diet in the Barrow area from 2007 to 2009: only 4% of all samples of the Glaucous Gull's diet contained avian eggs (E. L. Weiser, pers. comm.). However, as predicted, nest survival

TABLE 3. Return rates of Semipalmated Sandpipers and Dunlins nesting in and outside the North Slope Borough landfill near Barrow, Alaska, 2005–2012. Return rates listed for 2004 provide an estimate for birds returning after the landfill fence was constructed in 2005 (see Fig. 2D).

	No. uniquely marked birds nesting		No. birds returning to same nesting location[a]		No. birds changing nesting location[b]		No. birds not seen[c]	
Year	inside	outside	inside	outside	inside	outside	inside	outside
Semipalmated Sandpiper								
2004	1	0	0 (0%)	—	0 (0%)	—	1 (100%)	—
2005	10	5	1 (10%)	1 (20%)	0 (0%)	0 (0%)	9 (90%)	4 (80%)
2006	6	2	3 (50%)	0 (0%)	0 (0%)	0 (0%)	3 (50%)	2 (100%)
2007	10	4	3 (30%)	1 (25%)	0 (0%)	1 (25%)	7 (70%)	2 (50%)
2008	8	4	5 (63%)	0 (0%)	0 (0%)	0 (0%)	3 (38%)	4 (100%)
2009	18	5	9 (50%)	0 (0%)	0 (0%)	0 (0%)	9 (50%)	5 (100%)
2010	18	6	8 (44%)	1 (17%)	1 (6%)	0 (0%)	9 (50%)	5 (83%)
2011	23	7	10 (43%)	2 (29%)	0 (0%)	1 (14%)	13 (57%)	4 (57%)
Dunlin								
2004	6	4	1 (17%)	0 (0%)	0 (0%)	1 (25%)	5 (83%)	3 (75%)
2005	5	0	2 (40%)	—	0 (0%)	—	3 (60%)	—
2006	12	4	7 (58%)	0 (0%)	0 (0%)	0 (0%)	5 (42%)	4 (100%)
2007	8	1	3 (38%)	0 (0%)	0 (0%)	0 (0%)	5 (63%)	1 (100%)
2008	4	1	2 (50%)	1 (100%)	0 (0%)	0 (0%)	2 (50%)	0 (0%)
2009	7	1	3 (43%)	0 (0%)	0 (0%)	0 (0%)	4 (57%)	1 (100%)
2010	6	2	0 (0%)	0 (0%)	0 (0%)	2 (100%)	6 (100%)	0 (0%)
2011	4	2	0 (0%)	0 (0%)	0 (0%)	0 (0%)	4 (100%)	2 (100%)

[a]Individuals returned to same nesting location (i.e., either inside or outside landfill) in subsequent year.
[b]Individuals switched nesting location (either inside to outside or outside to inside landfill) in subsequent year. Column headings "inside" and "outside" refer to the first year's nesting location.
[c]Individuals not observed nesting within the landfill study plot in subsequent year.

increased in 2010 and 2011 when human food and other organic matter were deposited in the landfill or gravel was not placed over waste regularly (Fig. 5, Table 2). Therefore, rates of predation by gulls may have been further lowered by access to organic waste within the landfill, which is likely far easier to obtain than the relatively hard-to-find shorebird nests. These results are consistent with a previous study that showed the percentage of garbage in the diet of nonbreeding Glaucous Gulls decreased from 2007 (43%) to 2008 (28%), when the NSB switched from depositing raw organic waste in the old landfill to depositing incinerated organic waste in the new landfill (Weiser and Powell 2011). Unfortunately, we did not monitor chick survival, and so do not know the effect gulls and other avian predators may have had on shorebird chicks hatching from nests in or near the landfill. Previous studies, however, suggest gulls may have a substantial effect on chick survival in some situations. For example, in 2007 and 2008, the percent composition of adult or juvenile shorebirds in the diet of Glaucous Gulls breeding near Barrow was estimated at 21–48% per year, with 5% of samples containing chicks, 12% adults, and 21% shorebirds of unknown age (Weiser and Powell 2011; E. L. Weiser, pers. comm.). Furthermore, in California, Ackerman et al. (2006) found California Gulls (*Larus californicus) switching from landfill waste* to shorebird chicks during the latter part of the nesting season. Besides affecting shorebirds, increased numbers of Glaucous Gulls may also adversely affect other fauna that constitute a large portion of their diet (e.g., lemmings, waterfowl chicks; Weiser 2010).

In addition to low predation by avian predators, high rates of nest survival may have been partially due to arctic fox control throughout the area. Although we did not identify nest predators in our study, we presume the significantly greater rates of nest survival inside the landfill in three of the eight years were due primarily to arctic foxes being excluded from inside the landfill, as all other predators, including weasels, ground squirrels, and birds could easily enter the landfill. We also have other circumstantial evidence that supports the notion that greater nest survival was due to the exclusion of foxes from the landfill. First, foxes are rarely observed during predator surveys but often depredate large numbers of arctic shorebird nests (Liebezeit and Zack 2008). Second, there is a direct correspondence between the lower nest-success rates outside the landfill in 2009 and a change to less effective trapping methods for the arctic fox in that year (Savory et al. 2009). Finally, in 2004, before the fence and fox control, nest survival was lower within the future landfill than outside. After the fence was constructed, nest survival was greater inside the landfill during each of the next eight years.

Previous studies of arctic shorebirds have detected seasonal patterns in nest survival, although these patterns have not been consistent (Smith and Wilson 2010). In our study, nest survival declined as the season progressed. Because this pattern was consistent both in and outside the landfill, it cannot be explained by the removal of arctic foxes. Other factors could explain this pattern, such as changes in the timing and availability of alternative prey (in relation to prey switching; Bêty et al. 2002, Smith and Wilson 2010) or changes in the quality and investment of the incubating parent(s) attending early and late nests. In the latter case, nests laid late in the season may be by individuals that are inexperienced or in poor condition, and thus at sites of poorer quality, or are inexperienced at entering and leaving a nest site, exposing it to a greater risk of predation (Blomqvist et al. 1997). Nests laid later may also be replacement nests (Naves et al. 2008, Gates et al. 2013), and chicks from such nests may be unlikely to survive to fledging (see Hill 2012), so adults may spend less resources on later nests and more resources on self-maintenance (Robertson 1995). Regardless of the reason for this seasonal decline in nest success, the lack of snow inside the landfill may afford birds additional benefits, allowing them to nest earlier and increasing nest survival. These same individuals may also be more likely to return in subsequent years, as apparent adult survival and return rates are associated with successful nesting (Gratto et al. 1985, Flynn et al. 1999, Hill 2012). Although we cannot rule out completely that the greater return rates inside the landfill were not an artifact of the preferences of the Semipalmated Sandpiper and Dunlin for drier habitats, the fact that return rates within the landfill were greater than return rates at all other shorebird plots (Semipalmated Sandpiper: 42% vs. 28%; Dunlin: 37% vs. 32%; RBL, unpubl. data) supports the notion that additional factors other than habitat preferences are influencing return rates within the landfill. Therefore, a positive feedback loop may exist with earlier snow melt leading to earlier initiation dates that may increase apparent survival of nests and adults, ultimately leading to greater nest densities.

Despite the overall lack of negative responses by shorebirds to the NSB landfill, we did detect a decline in the density of Dunlin nests within the landfill following waste deposition. During the last two years of this study, we failed to document any marked Dunlin returning to nest inside the landfill. We do not know if these declines are due to the species being negatively affected by the landfill, low adult survival due to processes occurring outside the breeding season, or simply adults choosing to nest outside of the study plot. But we did not note similar declines in nest density in our other shorebird plots, although return rates have declined slightly since 2005 (RBL, unpubl. data). More research is needed to evaluate whether this trend continues and whether the NSB landfill has other long-term effects on nesting shorebirds.

The paucity of negative responses of shorebirds to the NSB landfill is likely due, at least in part, to the NSB personnel reducing the environmental effects of the landfill on nesting birds. Our results indicate that if procedures to reduce the attraction of predators to landfills (e.g., constructing fox-proof fences and incinerating or covering organic waste) are implemented, the indirect effects on nesting birds can be minimized. Furthermore, with appropriate management of landfills, waste consumption by gulls will likely decline, depressing the gull's fledging rates and ultimately its rate of population growth (Weiser and Powell 2010, 2011). With fewer gulls, the impact on shorebirds and other fauna in the area will likely be reduced. However, the results of our study should be generalized to other sites in the Arctic with caution. For example, our study took place in one of the largest towns in arctic Alaska, with the personnel and funding for procedures aimed at discouraging predators. Landfills elsewhere in arctic Alaska are not all managed the same, so it is unclear how these landfills affect predator populations, and thus measures of shorebird reproduction. The removal of foxes during our study may also make this study less generalizable, though we suspect that our conclusions would have been even more dramatic under more natural conditions. We suspect that differences in predation rates inside and outside the landfill would have been even greater, and that estimates of nest density and return rates outside the landfill would have been biased low because of nests failing prior to being found. Additional study is needed to evaluate how landfills, regardless of construction and operational procedures, affect arctic birds during chick-rearing, as well as other local fauna.

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