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Research Article

Sanitary Waste Landfill Effects on an Invasive Wild Pig Population

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ABSTRACT Being opportunistic omnivores, wild pigs (*Sus scrofa*) readily feed on edible garbage. Given the presence of substantial volumes of edible food waste, large multi-county and regional municipal sanitary waste landfills constitute attractive forage resources for pigs, providing a year-round anthropogenic source of potentially high-quality forage. Our objective was to assess the effects that a large regional landfill has on the local pigs foraging in that facility's waste disposal cells. The landfill, located on the United States Department of Energy's Savannah River Site (SRS) in South Carolina, USA, became operational in 1998 and pigs began foraging there in 2001. By 2009 >100 pigs/night were observed foraging in the landfill, suggesting landfill establishment may have important consequences for population dynamics, public safety, and disease transmission. We evaluated changes in body mass, fetal litter size, numbers of pigs removed, and wild pig-vehicle collisions (WPVCs) before (1980–2000) and after (2001–2019) pigs began foraging in the landfill on SRS. Body mass during the after period increased to a greater extent for pigs in the vicinity of the landfill compared to pigs on the rest of SRS. Fetal litter size increased for pigs in the vicinity of the landfill, whereas it remained unchanged on the rest of SRS. Our density surrogate (number of pigs harvested) increased around the landfill during the after period by 2.9 times, whereas on the rest of the site it only increased by 53%. No WPVCs occurred adjacent to the landfill before 2001, but WPVCs increased along the 2 major roads bordering the landfill after 2001. Effects of sanitary waste landfills on wild pig populations scavenging there can present unique challenges to population management, control, public safety, and disease transmission. Potential approaches to address these challenges could be exclusion fencing to prevent access to the landfill's waste disposal cells or enhanced placement of waste cell covers to reduce access.

KEY WORDS body mass, feral swine, garbage, landfill, litter size, scavenging, South Carolina, *Sus scrofa*, vehicle collision, wild pig.

Wild pigs (*Sus scrofa*), native to parts of Europe, Asia, and North Africa, have spread across much of the globe, largely as a result of translocation by humans. Wild pigs cause extensive ecological and economic damage to natural and anthropogenic environments in the introduced and native portions of this species' global range (Mayer 2009*a*). In the portion of that range where wild pigs are not native, the Species Survival Commission of the World Conservation Union listed wild pigs among the 100 worst invasive alien species in the world (Lowe et al. 2000). The term wild pig collectively encompasses the 3 wild-living forms of *Sus scrofa*, including Eurasian wild boar, feral pigs (wild pigs solely of domestic ancestry), and hybrids between these 2 forms (Keiter et al. 2016).

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Wild pigs are opportunistic omnivores (Ditchkoff and Mayer 2009, Ballari and Barrios-Garcia 2014). The ability of this invasive species to survive on almost anything edible is one of the primary reasons it has been so successful in establishing new populations in the introduced portions of the species' global range. The typical percent composition of material by volume in wild pig diets includes approximately 91% plant material, 7% animal material, and 2% other material (Schley and Roper 2003, Ditchkoff and Mayer 2009, Ballari and Barrios-Garcia 2014). The specific composition of the diet among wild pig populations is largely dependent upon what foods are available in their local area at any point in time (Schley and Roper 2003, Ditchkoff and Mayer 2009, Ballari and Barrios-Garcia 2014).

Wild pigs have been reported to feed on garbage (Hanson and Karstad 1959, Henry and Conley 1972, Hafeez et al. 2008, Cahill et al. 2012). This has been documented in a number of locations to include edible (e.g., discarded food waste) and non-food (e.g., diapers, paper, plastic, polyethylene bags, rubber bands) garbage (Hafeez et al. 2008, Ditchkoff and Mayer 2009). The source and volume of garbage accessed by wild pigs varies from individual garbage containers to larger garbage dumps and regional landfills (Henry and Conley 1972, Cahill et al. 2012, Podgórski et al. 2013). Given the presence of substantial volumes of edible waste in multi-county regional municipal sanitary waste landfills (e.g., the Guadalupe Landfill, San Jose, CA, USA; Seminole County Landfill, Orlando, FL, USA), these landfills constitute attractive forage resources for large numbers (e.g., ~3,000 at 1 location) of wild pigs (Berry 1992, Do 2017). Compared to the natural environmental food base, the large volume of edible garbage present in landfills has the potential to provide a year-round anthropogenic source of high-quality forage for pigs (Hafeez et al. 2008, Leib et al. 2016). As such, edible garbage can be locally more abundant and potentially of higher nutritional quality and thus more preferred than local, seasonal, natural foods in their environment (Hafeez et al. 2008, Ditchkoff and Mayer 2009).

The quality and amount of forage resources can affect wild pig growth, reproduction, and population biology parameters (Matschke 1964, Schley and Roper 2003, Ditchkoff and Mayer 2009). Differential use of certain forage resources among sex and age classes has also been reported for wild pigs (Ditchkoff and Mayer 2009, Ballari and Barrios-Garcia 2014).

In this study we predicted that the establishment of a regional landfill would affect the productivity, individual condition, and demographics of the local wild pigs. More specifically, we predicted that wild pigs in the area immediately surrounding the landfill (i.e., impact area) would have greater body mass, litter sizes, and density than those distant from it (i.e., control area), and that these effects, combined with differential resource use among ages and sexes, would result in differences in sex ratio and age structure of wild pigs on impact and control areas. Additionally, we predicted that wild pig-vehicle collisions (WPVCs) would be greater on the impact area compared to the control area during the after-landfill period compared to before, but that the temporal pattern of WPVCs would not differ between control and impact areas during either time period.

STUDY AREA

We conducted this study from 1980–2019 on the Savannah River Site (SRS), a federal nuclear facility operated by the United States Department of Energy (DOE). The SRS encompassed 803 km^2 in western South Carolina (Fig. 1). The SRS was located entirely within the upper Atlantic Coastal Plain with elevations ranging from 20–130 m. The climate was humid subtropical, with a mean annual temperature of 18°C and mean annual rainfall of 122.5 cm. From June through September, extreme high temperature exceeded 40°C, and extreme low temperatures were observed in January and December (i.e., −19.4°C and −13.9°C, respectively). Greatest mean monthly rainfall occurred in July (13.1 cm) and least occurred in November (6.6 cm). We defined seasons as winter (Dec–Feb), spring (Mar–May), summer (Jun–Aug), and fall (Sep–Nov). Approximately 95% of SRS lands were undeveloped with the remainder of the site occupied by DOE industrialized areas. Managed pine (*Pinus* spp.) forests dominated the SRS landscape, which included several riparian corridors composed of bottomland hardwood forest and forested swamp. In addition, pockets of upland hardwood forest and mixed pine-hardwood forest, and isolated Carolina bay wetlands were scattered throughout the site. Large wildlife species present included white-tailed deer (*Odocoileus virginianus*), coyote (*Canis latrans*), bobcat (*Lynx rufus*), wild turkey (*Meteagris gallopava*), and American alligator (*Alligator mississippiensis*; Kilgo and Blake 2005).

The introduced population of wild pigs on the SRS has been in existence for >80 years, having originated from free-ranging domestic pigs that went feral possibly as early as the eighteenth century (Mayer and Brisbin 2012). Beginning in the mid-1970s, this population was hybridized with illegally released animals exhibiting mixed wild boar and feral pig characteristics (Mayer and Brisbin 2012, Mayer et al. 2020). Based on both morphological and genetic characteristics, the wild pig population on SRS during the study was composed of wild boar × feral pig hybrids (Mayer and Brisbin 2012). Since the early 1950s, wild pigs affected the SRS through rooting damage, forest resource damage, disease transmission, predation of native species, competition with native wildlife, vehicle collisions, hazards to SRS personnel, and property damage. Between 1956 and the present, the population was managed by DOE through annual public deer hunts (during which wild pigs were legally harvested), a contract control program, and control activities conducted by the United States Forest Service, Savannah River. These efforts entailed lethal removal of wild pigs through shooting, trapping, and hunting with dogs (Mayer and Brisbin 2012).

The Three Rivers Solid Waste Authority (TRSWA) operated a 9-county regional federal Resource Conservation and Recovery Act Subtitle D sanitary waste landfill on the SRS (DOE 1995). The SRS was divided into wildlife management compartments, and the TRSWA landfill (i.e., the landfill) was completely encompassed within wildlife compartment (WC) 20, which was 3,242 ha in size (Fig. 1). The landfill began waste disposal operations in late 1998 and continued operation through the duration of the study. The landfill encompassed 134 ha of open ground (its overall footprint), surrounded by forest, with the active waste disposal cells (i.e., garbage disposal pits) occupying 28 ha within the footprint (Fig. 1). The landfill received about 907 metric tons of waste per day, or about 226,796 metric tons/year (TRSWA 2019), which variously included household waste, trash, refuse, paper, rubbish, industrial waste, ashes, appliances, food waste and other materials (DOE 1995). Neither the landfill footprint nor the waste disposal cells were fenced, and forest management in the remainder of WC 20 continued consistent with management on the rest of SRS.

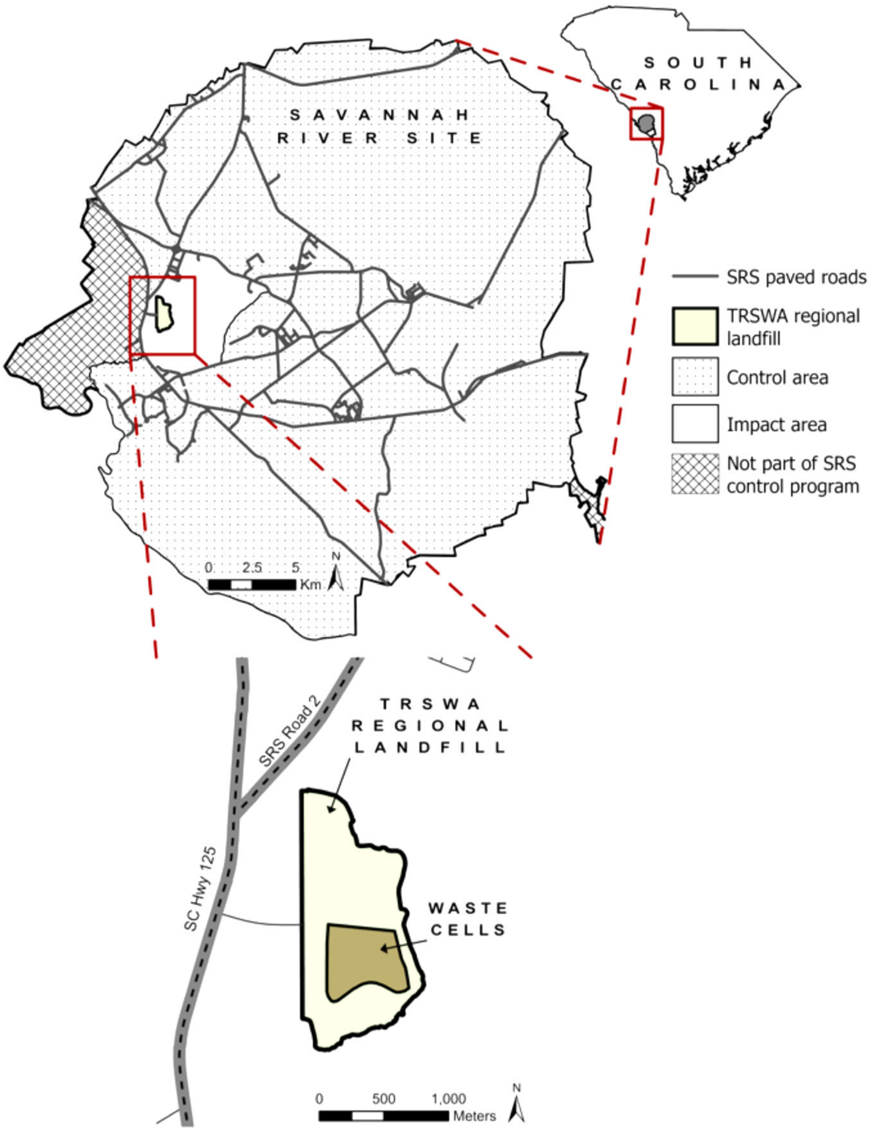

Figure 1. Location of the Savannah River Site (SRS) in South Carolina, USA, and location of the Three Rivers Solid Waste Authority (TRSWA) regional landfill, with waste disposal cells, within Wildlife Compartment 20, labeled as impact area, on the SRS. Cross-hatched area west of the landfill is on SRS property but is managed by the South Carolina Department of Natural Resources and therefore not within the SRS wild pig control program.

In late 2001 wild pigs were observed foraging in the landfill's waste disposal cells for the first time (C. W. Covington, TRSWA, personal communication). By 2009 >100 pigs/night were frequently observed foraging in the landfill (Mayer and Brisbin 2012). Based on global positioning system (GPS) fixes from radio-collared pigs, this extensive use of the landfill by wild pigs as a forage resource continued through 2016 (Fig. 2; J. C. Kilgo, USDA Forest Service, unpublished data), and anecdotal observations indicate that it continued through the end of 2019 (T. T. Mims, U.S. Forest Service, personal communication).

METHODS

Data Collection

We obtained data from SRS harvest records and the SRS control program, collected by SRS personnel. Data from each pig included its location and date of removal, body mass, sex, and age class (i.e., piglet, juvenile, yearling, subadult, and adult as defined in Mayer and Brisbin 2012). Workers also recorded fetal litter count for all pregnant females taken during public hunts and a subsample of those removed by contractors. We considered number of wild pigs removed from an area an approximate indicator of density, following Massei et al. (1997), Merli and Meriggi (2006), and Massei et al. (2015). We recognize that removals may not accurately reflect true density; however, Imperio et al. (2010) reported a significant correlation between harvest and actual counts of wild pigs in Italy. During annual public deer hunts, each WC was hunted only 1 day/year. Although contract trappers may have focused somewhat more effort in areas of greater density, contractors were responsible for implementing the control program across SRS and therefore were unable to concentrate disproportionate effort in any single area. We acknowledge that any bias in contractor effort could result in greater removals from that area and

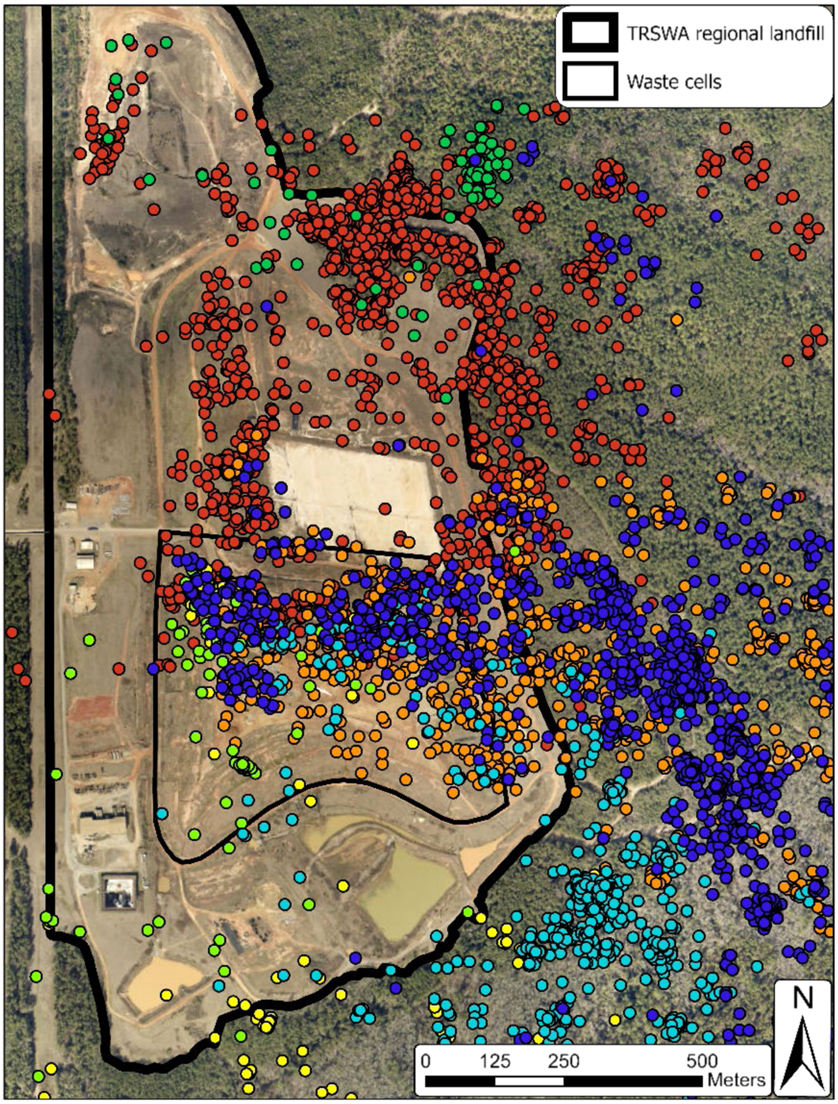

Figure 2. Color-coded global positioning system (GPS) locations of 1 subadult or adult female from each of 7 wild pig sounders GPS-collared in and around the Three Rivers Solid Waste Authority (TRSWA) regional landfill, on the Savannah River Site, South Carolina, USA, 1 January–20 August 2016. Collars were programmed to acquire GPS fixes at 2-hour intervals. The concentration of locations in the central portion of the landfill footprint is in the waste disposal cells (J. C. Kilgo, unpublished data).

potentially exaggerate the appearance of a difference in density on impact and control areas. If such bias occurred, we feel that it would provide further indication that density was greater in those areas, even if not to the precise extent indicated by the data. Thus, lacking actual density estimates, the number of pigs removed represented a reasonable approximation of wild pig density at SRS because removal effort was generally similar across the site during the study period owing to the widespread nature of the damage caused by wild pigs. Similarly, we used sex and age composition of removed pigs to approximate sex ratio and age structure of the population. Although older age classes may be less susceptible to capture in traps (Mayer 2009*b*), any such bias would have been uniform across our dataset because the SRS control program targeted all age and sex classes consistently through time and across the entire SRS, and therefore would not have influenced our comparisons.

We compiled SRS-wide WPVCs records between 1980 and 2018 from data collected by SRS law enforcement and contractors. These data included date, location, sex and age class of the pig, and time of day.

Data Analysis

Based on a before-after-control-impact (BACI; Stewart-Oaten et al. 1986) design, we compared body mass and fetal litter size of pigs from WC 20, containing the landfill (i.e., impact area, encompassing 3,242 ha), with that of pigs from all other compartments on SRS (i.e., control area, encompassing 70,199 ha), before (1980–2000) and after (2001–2019) pigs were actively foraging in the landfill. We developed mixed-effects analysis of variance (ANOVA) models separately for body mass and litter size to test for differences in means between treatment areas (impact and control areas) between time periods (before and after time periods). In both models, we fit treatment area, time period, and their interaction (i.e., the BACI effect) as fixed effects to explicitly test for differences. In the body mass model, we also included fixed effects for age and sex to control for increases in body mass as pigs age and differences between sexes. Similarly, we included a fixed effect for age in the litter size model to account for potential increases in litter size as pigs age. On the SRS, most (92%) litters are produced by females in the yearling and older age classes after a 115-day gestation period (Mayer and Brisbin 2012). We included only litters from yearling and older females (≥1 yr old) because of inadequate sample sizes in younger age classes (i.e., piglets: $n = 1$; juveniles: $n = 6$). We fit treatment area (impact and control) and year as random intercepts in each model to account for unbalanced sample sizes and non-independence of observations within each treatment area (Schielzeth and Forstmeier 2009). We evaluated model fit and assumptions by examining residual distributions for each model. Based on a visual examination of the distribution of body mass model residuals, we used a square root transformation of body mass to normalize model residuals. Distribution of litter size model residuals indicated no deviation from normality, so we did not apply any transformation to litter size values.

We used pairwise contrasts to assess effects of landfill establishment on body mass and litter size in 2 ways. First, we developed pairwise before versus after landfill contrasts to determine if overall body mass and litter size means for impact and control areas differed between before and after time periods. Second, we developed pairwise impact versus control contrasts to determine if the magnitude of before versus after landfill differences in mean body mass and litter size differed between impact and control areas (i.e., was the magnitude of difference in before vs. after landfill means, or the BACI effect, consistent between impact and control areas?).

We developed tests of equal or given proportions (Zar 1984) to compare age and sex class composition between treatment areas during each time period separately for pig removal and WPCV datasets. Because our main interest was determining whether number of pigs removed and WPVCs observed (total numbers and by sex and age class) in the impact area differed from the control area, we tested hypotheses that proportions (based on observed numbers) in the impact area were not equal to those in the control area (i.e., 2-tailed tests). Accordingly, we used the observed proportion of pigs removed from the control area to approximate the *a priori* expected proportion in the impact area. For example, if the observed proportion of male pigs removed in the control area during the before landfill time period was 0.25, we tested the null hypothesis that the proportion of male pigs removed in the impact area during the before landfill time period was not equal to 0.25. Finally, we used calculated effect sizes for pairwise differences in proportions using Cohen's h (Cohen 1988).

For the removal dataset, we compared proportions of pigs removed between time periods for each treatment area (e.g., control-before-total vs. control-after-total), proportions of males and females removed between treatment areas during each time period (e.g., control-before-males vs. impact-before-males), and proportions of specific age classes removed between treatment areas during each time period (e.g., control-before-adult vs. impact-before-adult). For the collision dataset, we only tested data during the after-landfill time period because no collisions occurred on the 2 major roads bordering the impact area (i.e., SC Highway 125 and SRS Road 2; Fig. 1) during the before landfill time period. Accordingly, we compared proportions of males and females involved in collisions between treatment areas during the after time period (e.g., control-after-male vs. impact-after-male), proportions of specific age classes involved in collisions between treatment areas during the after time period (e.g., control-after-adult vs. impact-after-adult), proportions of collisions between treatment areas during individual months (e.g., control-after-May vs. impact-after-May), and proportions of collisions between treatment areas during individual seasons (e.g., control-after-spring vs. impact-after-spring).

We conducted all analyses in the R statistical environment (R Core Team 2020) using the contributed packages lme4 (Bates et al. 2015) to fit mixed-effects ANOVAs, emmeans (Lenth et al. 2020) for pairwise contrasts, the R base function prop.test for chi-square tests of proportions, and the contributed package pwr (Champely et al. 2020) to calculate effect sizes for proportion tests. We considered pairwise before versus after time period contrasts significant if 90% confidence intervals of contrast estimates did not overlap, and pairwise impact versus control contrasts significant if 90% confidence intervals did not overlap zero. Similarly, we considered pairwise differences in before versus after landfill proportions significant if 90% confidence intervals of proportion differences did not overlap zero.

RESULTS

We compiled body mass data on 11,296 pigs harvested between 1980 and 2019 (control-before = 8,543; control-after = 2,010; impact-before = 529; impact-after = 214). Overall, body mass averaged 34.0 ± 33.1 kg (SD) and ranged 0.5–189.0 kg. Body mass was affected by age ($\chi^2 = 74{,}505.4$, $P \leq 0.001$), sex ($\chi^2 = 137.7$, $P \leq 0.001$), and the interaction between treatment area and time period (i.e., the BACI effect; $\chi^2 = 10.9$, $P \leq 0.001$; Table 1). Pairwise before- versus after-landfill contrasts indicated mean body mass was greater during the after time period for both treatment areas (Fig. 3), but pairwise impact versus control contrasts indicated the magnitude of the BACI effect was significantly larger for the impact area compared to the control area (i.e., the magnitude of after-landfill increase in body mass was larger in the impact area compared to the control area; Table 2).

Our data included fetal counts of *in utero* litters from 799 pregnant pigs harvested between 1980 and 2019 (i.e., control-before = 502; control-after = 236; impact-before = 39; impact-after = 22). Overall, litter sizes averaged 6.2 ± 1.9 and ranged 1–14. Litter size was affected by age ($\chi^2 = 5.6$, $P = 0.06$) and the interaction between treatment

Table 1. Parameter estimates, 90% confidence intervals (CI), and associated *P*-values from analysis of variance models comparing wild pig body mass and fetal litter size between control and impact areas before and after wild pigs began foraging in the Three Rivers Solid Waste Authority regional landfill, 1980–2019, Savannah River Site, South Carolina, USA.

	Body mass (kg)			Litter size		
Parameter	**β**	**90% CI**	***P***	**β**	**90% CI**	***P***
(Intercept)	8.97	8.91 to 9.03	$\leq$0.001	6.17	5.96 to 6.39	$\leq$0.001
Treatment area (impact area)	−0.10	−0.20 to −0.01	0.083	−0.23	−0.80 to 0.33	0.490
Time period (after)	0.43	0.39 to 0.47	$\leq$0.001	0.07	−0.19 to 0.33	0.650
Sex (male)	0.22	0.19 to 0.26	$\leq$0.001			
Age (subadult)	−1.29	−1.35 to −1.24	$\leq$0.001	0.11	−0.16 to 0.38	0.510
Age (yearling)	−2.39	−2.44 to −2.34	$\leq$0.001	−0.33	−0.63 to −0.03	0.072
Age (juvenile)	−4.05	−4.10 to −3.99	$\leq$0.001			
Age (piglet)	−6.77	−6.81 to −6.72	$\leq$0.001			
Treatment area (impact area) × time period (after)	0.28	0.14 to 0.42	$\leq$0.001	1.15	0.25 to 2.04	0.035

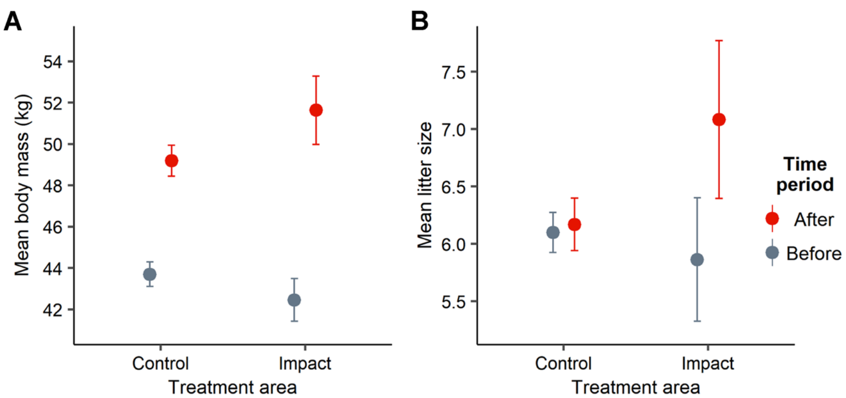

Figure 3. Differences in mean body mass (A) and litter size (B) of wild pigs sampled on impact and control areas on Savannah River Site, South Carolina, USA, before (1980–2000) versus after (2001–2019) wild pigs began foraging in the Three Rivers Solid Waste Authority regional landfill.

area and time period (the BACI effect; $\chi^2 = 4.43$, $P = 0.04$; Table 1). Pairwise before- versus after-landfill contrasts indicated mean litter size was larger during the after time period in the impact area but not the control area (Fig. 3), and pairwise impact versus control contrasts indicated the magnitude of the BACI effect was significant for the impact area but not the control area (Table 2). Specifically, fetal litter size in the impact area increased from 5.9 during the pre-landfill period to 7.1 during the after-time period, a difference of 1.2 fetuses per litter (Fig. 3).

Our removal data included 23,983 pigs (i.e., control-before = 8,445; control-after = 12,939; impact-before = 528; impact-after = 2,071). The proportion of pigs removed was lower in impact area compared to the control area during the before time period (proportion difference = 0.192; 90% CI = 0.177–0.206) but was greater in the impact area compared to the control area during the after period (proportion difference = −0.192; 90% CI = −0.206 to −0.177). The proportion of pigs removed from the impact area increased by 2.92 times between before and after time periods, whereas the proportion removed on the control area only increased by 53% between before and after time periods (Fig. 4; Table 3). Our removal data included age and sex class for 11,804 and 23,983 pigs, respectively, harvested between 1980 and 2019 (available online in Supporting Information Tables S1 and S2). Sex ratios of removed pigs did not differ between impact and control areas during either time period (Table 3). There were no consistent differences in proportion of age classes removed between the impact and control areas during either time period (Table 3), but there was evidence that a greater proportion of adults and piglets were removed during the after time period in the impact area compared to the control area (Table 3).

Our data included records for 496 WPVCs documented on SRS roads between 2000 and 2018 (Supporting Information Tables S3 and S4). No WPVCs occurred adjacent to the impact area during the before time period, with the first occurring in 2003. From 2003–2018, 20 WPVCs occurred adjacent to the impact area (Fig. 5). Sex ratio of pigs involved in WPVCs did not differ between impact and control areas (Table 4). Age classes of pigs

Table 2. Pairwise treatment versus control contrasts of before-after-control-impact effects for body mass and litter size of wild pigs before (1980–2000) and after (2001–2019) they began foraging in the Three Rivers Solid Waste Authority regional landfill on Savannah River Site (SRS), South Carolina, USA. Impact area is wildlife compartment 20 surrounding the landfill and control area is the rest of SRS.

Response	Time period	Contrast	Contrast estimate (90% CI)
Body mass	Before	Impact-control	−1.24 (−2.41 to −0.07)
	After	Impact-control	2.44 (0.62 to 4.25)
Litter size	Before	Impact-control	−0.24 (−0.80 to 0.33)
	After	Impact-control	0.91 (0.19 to 1.63)

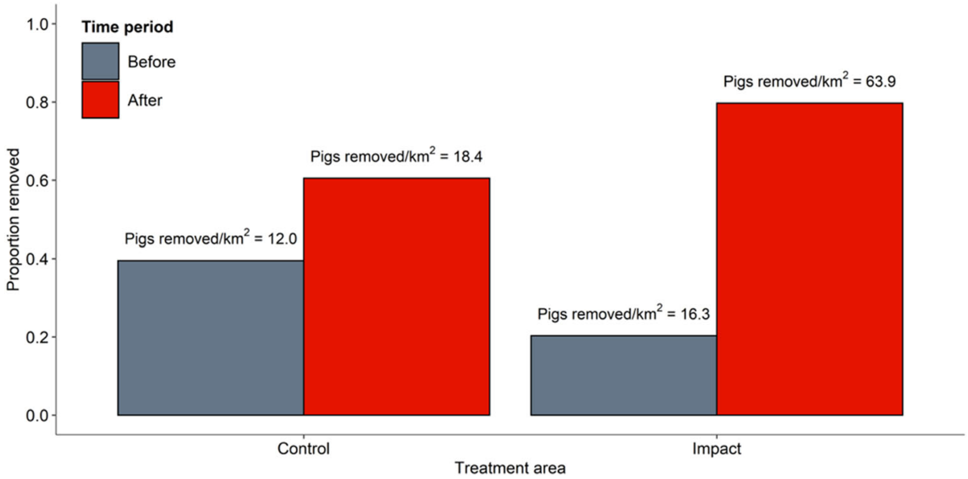

Figure 4. Proportions of wild pigs removed from control and impact areas on the Savannah River Site, South Carolina, USA, before (1980–2000) and after (2001–2019) they began foraging in the Three Rivers Solid Waste Authority regional landfill.

involved in WPVCs did not differ between impact and control areas, but there was evidence for marginally higher and lower numbers of adult and yearling pigs involved in WPVCs, respectively, around the impact area compared to the control area (Table 4). Documented WPVCs occurred during every month and season of the year, with monthly and seasonal peaks in the impact area during May and September and spring and fall, respectively, compared to the

Table 3. Pairwise comparisons of proportional differences in sex and age class composition, with 90% confidence intervals (CI), Cohen's *h* effect size for differences in proportions and associated *z*-scores (*h* [*z*-score]), and percent difference in proportions of wild pigs removed from impact and control areas (wildlife compartment 20 containing the Three Rivers Solid Waste Authority regional landfill and the rest of Savannah River Site, respectively) on Savannah River Site, South Carolina, USA, before (1980–2000) and after (2000–2019) wild pigs began foraging in the landfill. Proportion differences for which the 90% confidence intervals did not overlap zero are indicated with asterisks.

Grouping factor	Time period	Treatment area	Proportion	Proportion difference (90% CI)	*h* (*z*-score)	% difference
Sex						
Male	Before	Control	0.526	−0.014 (−0.052 to 0.024)	−0.03 (0.57)	−3%
		Impact	0.512			
	After	Control	0.465	0.010 (−0.045 to 0.066)	0.02 (0.25)	2%
		Impact	0.475			
Female	Before	Control	0.474	0.014 (−0.024 to 0.052)	0.03 (0.57)	3%
		Impact	0.488			
	After	Control	0.535	−0.010 (−0.066 to 0.045)	−0.02 (0.25)	−2%
		Impact	0.525			
Age						
Adult	Before	Control	0.174	−0.057 (−0.081 to −0.032)*	−0.16 (3.29)	−49%
		Impact	0.117			
	After	Control	0.265	0.179 (0.124 to 0.234)*	0.38 (6.02)	40%
		Impact	0.444			
Subadult	Before	Control	0.120	0.027 (0.001 to 0.054)*	0.08 (1.78)	18%
		Impact	0.147			
	After	Control	0.222	0.029 (−0.019 to 0.078)	0.07 (1.01)	12%
		Impact	0.251			
Yearling	Before	Control	0.142	−0.023 (−0.048 to 0.002)	−0.07 (1.40)	−19%
		Impact	0.119			
	After	Control	0.184	−0.006 (−0.050 to 0.036)	−0.02 (0.18)	−3%
		Impact	0.178			
Juvenile	Before	Control	0.146	−0.017 (−0.044 to 0.008)	−0.05 (1.07)	−13%
		Impact	0.129			
	After	Control	0.179	−0.048 (−0.086 to −0.009)*	−0.13 (1.83)	−37%
		Impact	0.131			
Piglet	Before	Control	0.418	−0.030 (−0.067 to 0.007)	−0.06 (1.32)	−8%
		Impact	0.388			
	After	Control	0.150	0.051 (0.006 to 0.095)*	0.13 (2.04)	25%
		Impact	0.201			
Totals						
Control	Before		0.395	0.210 (0.202 to 0.218)*	0.42 (43.5)	53%
	After		0.605			
Impact	Before		0.203	0.594 (0.575 to 0.612)*	1.27 (42.8)	292%
	After		0.797			

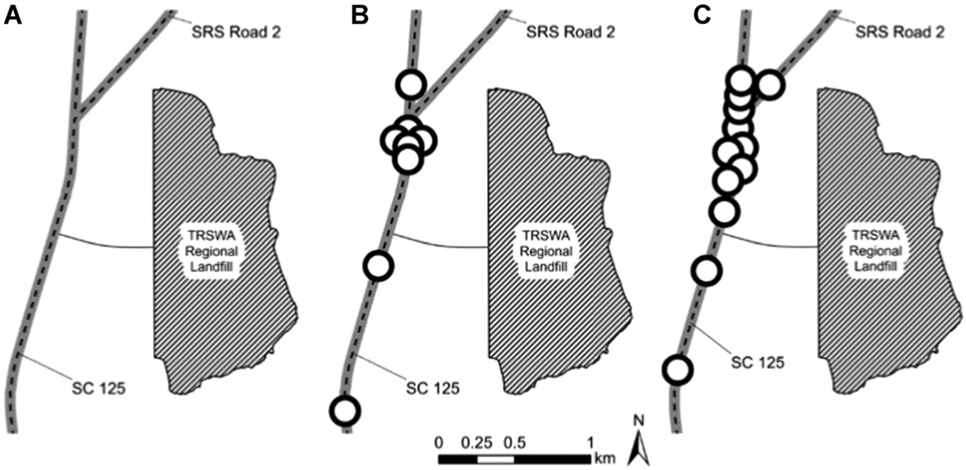

Figure 5. Illustration of the increase in wild pig-vehicle collision sites along South Carolina Highway 125 and SRS Road 2 adjacent to the Three Rivers Solid Waste Authority (TRSWA) regional landfill on the Savannah River Site (SRS), South Carolina, USA, during 3 time periods: A) 1980–1999, B) 2000–2009, and C) 2010–2019. Wild pigs were present throughout the Savannah River Site area depicted from 1980 through 2019.

Table 4. Pairwise comparisons of proportional differences in sex and age class composition, with 90% confidence intervals (CI), Cohen's *h* effect size for differences in proportions and associated *z*-scores (*h* [*z*-score]), and percent difference in proportions of wild pig-vehicle collisions along South Carolina Highway 125 and Savannah River Site (SRS) Road 2 adjacent to Three Rivers Solid Waste Authority regional landfill (impact area) and for the rest of SRS (control area), South Carolina, USA, between 2000 and 2018.

Grouping factor	Treatment area	Proportion	Proportion difference (90% CI)	*h* (*z*-score)	% difference
Sex					
Male	Control	0.557	0.064 (−0.107–0.235)	0.13 (0.48)	10%
	Impact	0.621			
Female	Control	0.443	−0.064 (−0.235–0.107)	−0.13 (0.48)	−17%
	Impact	0.379			
Age					
Adult	Control	0.081	0.126 (−0.018–0.269)	0.37 (1.97)	61%
	Impact	0.207			
Subadult	Control	0.289	−0.048 (−0.201–0.106)	−0.11 (0.34)	−20%
	Impact	0.241			
Yearling	Control	0.238	−0.100 (−0.228–0.029)	−0.26 (1.01)	−72%
	Impact	0.138			
Juvenile	Control	0.229	0.012 (−0.135–0.159)	0.03 (0.00)	5%
	Impact	0.241			
Piglet	Control	0.163	0.009 (−0.119–0.138)	0.02 (0.00)	5%
	Impact	0.172			

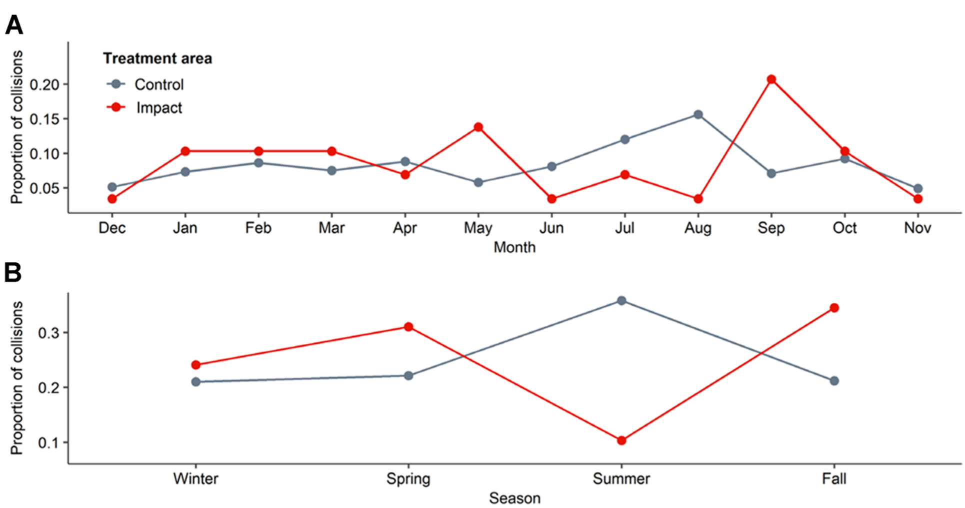

Figure 6. Proportions of monthly (A) and seasonal (B) wild pig-vehicle collisions along South Carolina Highway 125 and SRS Road 2 adjacent to Three Rivers Solid Waste Authority regional landfill (impact area) and for the rest of Savannah River Site (control area) in South Carolina, USA, after wild pigs began foraging in the landfill (2000–2019).

control area (Fig. 6). There were no clear monthly or seasonal differences in WPVCs between impact and control areas (Supporting Information Table S5). Of the 15 WPVCs for which a time of the accident was available, 14 were within 1 hour before or after sunrise. The latest accident occurred 2.5 hours after sunset.

DISCUSSION

Landfills have various environmental effects (Maheshwari et al. 2015). Our findings concur with previous work documenting specific effects on various wildlife species foraging in landfills, including increases in mean body mass, reproductive output, population density (e.g., herring gull [*Larus argentatus*], Pons and Migot 1995; glaucous gulls [*Larus hyperboreus*], Weiser and Powell 2010; kelp gulls [*Larus dominicanus*], Lenzia et al. 2019), and changes in behavioral patterns (white stork [*Ciconia ciconia*], Blanco 1996). Although we remain uncertain as to why body mass increased across SRS as a whole, the marked increase in body mass we observed among pigs foraging in the landfill has 2 potential repercussions. First, increased body mass in sexually mature female wild pigs is correlated with increased litter size (Comer and Mayer 2009), which we also observed. Secondly, a larger body mass represents an increased safety risk with respect to WPVCs. The heaviest female (181 kg) and male (204 kg) body masses ever recorded for wild pigs at SRS were 2 animals harvested in 2017 on a portion of SRS that is public wildlife management area land (Fig. 1) directly across South Carolina Highway 125 adjacent to the landfill (M. B. Caudell, South Carolina Department of Natural Resources, personal communication). The 20% increase in litter size we observed (an increase of 1.2 fetuses/litter over the control area average of 5.9) could have a large effect on population size over a relatively short period (e.g., 10 yr), assuming the additional fetuses survived at the same rate as the rest of the litter. Such increased recruitment would represent a significant challenge to management efforts aimed at reducing the size of a wild pig population.

Between 1980 and 2019, the wild pig population increased in size across the entire SRS (Mayer et al. 2020), as evidenced in our data. The extent of increase was much greater on the impact area than the control area, particularly among the adult and piglet age classes, the latter of which is consistent with the increased litter size observed on the impact area after landfill establishment. Research at SRS conducted either prior to the establishment of the landfill or in areas away from it reported densities of 1–6 pigs/km^2 (Mayer and Brisbin 2012, Keiter et al. 2017, Schlichting et al. 2020). During 2014, a motion-sensitive camera survey in the area surrounding the landfill estimated density there to be 16.5 pigs/km^2 (J. C. Kilgo, unpublished data), 2.75 times greater than the highest previously reported density and an increase in density that corresponds well with the 2.92 times increase in removals reported herein. Therefore, we believe the significant increase in the number of wild pigs harvested on the impact area compared to the control area, regardless of its precision, resulted from both a general population increase across SRS and an increase in the number of pigs present around the landfill.

Although data on traffic patterns around the landfill are unavailable, the increase in WPVCs we observed there cannot be attributed to increased traffic flow. First, the SRS employee population and associated traffic volume have decreased from the 1980s through the present; increased traffic associated with landfill operation (e.g., garbage trucks) was offset by the overall reduction in employee traffic on SRS during this period (Kilgo and Blake 2005, DOE 2020). Second, traffic associated with the landfill itself occurred during daylight hours when the landfill operates, which is not when most WPVCs occurred. Because wild pigs have not been observed in the waste disposal cells during daylight hours, presumably because of human activity there, we assume that the animals involved in accidents around sunrise were leaving the landfill and around sunset were entering the facility. Locations from GPS fixes from radio-collared pigs indicating nocturnal use of the waste disposal cells corroborates this assumption (J. C. Kilgo, unpublished data). Finally, WPVCs have occurred on the 225 km of maintained primary roads on SRS since the late 1960s (Mayer and Johns 2007) and were documented and reported annually by SRS law enforcement and contractors. Between 1980 and 2002, no WPVCs occurred on the 5.6 km of roads adjacent to the landfill. After the first WPVC occurred in 2003, numbers of WPVCs began to increase along the adjacent roads bordering the landfill to the extent that the SRS erected wild pig crossing signs along that roadway on either end of the landfill's footprint in 2012.

In addition to an increase in number of WPVCs, presence of the landfill on SRS has contributed to the problem of WPVCs there in other ways. Pigs are larger around the landfill and adults (the largest age class) are more frequently involved in WPVCs there. Larger and heavier pigs likely result in more severe consequences from such accidents (Mayer and Johns 2007), highlighting the increased safety risk to humans from pigs with increased body mass crossing roads to access the landfill. In addition, WPVCs on the SRS occur more frequently at the road crossings of stream and drainage corridors, especially where steel guardrails and bridge walls act as barriers to pigs attempting to leave the roadway in front of oncoming vehicles (Mayer and Johns 2007, Beasley et al. 2014). None of the roads bordering the landfill have any of these natural movement corridors or physical road barriers, suggesting the costs of movement in the absence of natural corridors are offset by the benefits of food resources provided in the landfill. Thus, the landfill has created a new location for WPVCs and those accidents may cause greater damage.

In general, allowing wild pigs to forage on garbage in a landfill creates several operational problems for the facility. Foraging activity by pigs roots up and exposes covered and decomposing waste in disposal cells (Berry 1992). The uncovered and scattered waste is also available to other local scavengers on the SRS (e.g., crows [*Corvus* spp.], vultures

[Cathartidae], gulls [*Larus* spp.], coyotes), causing further scattering of the waste. Wild pig rooting on the sides or slopes of landfills can also lead to erosion and slumping of the landfill cap or cover (Van Hoof 2019). Collectively, such damage caused by foraging pigs requires cleanup of dispersed and unearthed food waste and repairs to the landfill cap (Mann 2016).

Potential disease or pathogen transmission to wild pigs can also result from these animals foraging in sanitary landfill waste disposal cells. For example, African swine fever virus (ASFV) currently is spreading across Eurasia, having reached Belgium in the west and China, Far East Russia, and the northern region of South Korea in the east (Spickler 2019, Gavier-Widén et al. 2020). Several credible scenarios exist for the introduction of ASFV into the United States (Golnar et al. 2019, Jurado et al. 2019). Based on the paths of transmission across Eurasia, a number of these scenarios involve wild pigs foraging in landfills (Costard et al. 2013, Brown and Bevins 2018). Elimination of ASFV from a wild pig population once it has become endemic is difficult (Gogin et al. 2013). The introduction of ASFV into a wild pig population can potentially result in transmission into local domestic herds, as has happened in Eurasia (Gavier-Widén et al. 2015). Such an outbreak of ASFV or other foreign animal diseases in domestic swine in the United States could cost billions of dollars in losses in headcount, productivity, or sales (Paarlberg et al. 2009, Pineda-Krch et al. 2010, Mayer 2018). Therefore, unrestricted wild pig access to food waste in landfills could have very serious consequences from disease transmission that can have broad biological and economic implications.

A variety of animals can be attracted to the concentrated foraging and shelter resources provided by municipal solid waste deposited in landfills. The effect of such concentrated resources on wild pig populations can present unique challenges to public safety, population control, and disease transmission. Although control efforts in the form of increased trapping and shooting could be intensified around landfills, complete elimination of pigs from the surrounding area is impossible given the extent of the populations surrounding many landfills and their capacity as a source for rapid recolonization. One solution would be to simply prevent pigs from accessing landfill resources by erecting an exclusion barrier of pig-proof fencing (e.g., Reidy et al. 2008, Doupé et al. 2010, Rattan et al. 2010). Upon accessing the landfill and learning that the landfill provides concentrated forage resources, individual wild pigs are likely to be more motivated to cross exclusion fences or other physical barriers to movement surrounding the landfill (Mayer 2018, Mitchell 2011, Ditchkoff and Bodenchuk 2020). Such a fence would require monitoring and maintenance to successfully function as a barrier. Another possible approach could involve minimizing the attractiveness or accessibility of the waste by placement of cover fill (i.e., soil) to a depth that would preclude rooting and foraging; however, wild pigs can root as deep as 120 cm for targeted forage resources (Mayer and Brisbin 2012), so maintaining such a daily cover depth may not be economically feasible. Placement of reusable tarps or other durable covers (e.g., Posi-Shell® environmental coatings; LSC, Apalachin, NY, USA) may also represent an option for excluding pigs.

MANAGEMENT IMPLICATIONS

Our research indicates that wild pigs are attracted to landfills with varying consequences for pigs and humans. The larger body mass and litter sizes of wild pigs foraging in a municipal solid waste landfill, which results in greater density and incidence of WPVCs, amplifies the difficulty of controlling wild pig populations around landfills. Thus, management should focus on exploring the relative cost and benefits of different exclusion methods, and ways to minimize the attractiveness of landfills to wild pigs.

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