Decline of novel ecosystems used by endangered species: the case of piping plovers, least terns, and aggregate mines

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Abstract. Sand and gravel mining creates novel ecosystems along the Platte, Loup, and Elkhorn rivers in Nebraska, USA. Piping plovers and least terns are state and/or federally threatened and endangered species, respectively, that nest and raise young at these sites and their derivatives. Despite hosting relatively large numbers of piping plovers and least terns for decades, an important question that has largely gone unaddressed is whether the industry that has produced these novel ecosystems is stable and will continue to produce habitat consistently in the future. We evaluated how the number, size, and spatial distribution of different site types hosting different numbers of nesting plovers and terns have changed over time and how current trends in the number of different site types will affect future habitat using a multi-state modeling approach. Overall area and total number of sites declined during the period 1993–2020. More important, one site type, traditional mines, are being replaced by another site type, modern mines, which host lower numbers of nests of both species. The difference between these two site types is primarily how waste sand is stored. Traditional mines store waste sand in spoil piles or plumes along the edge of a lake created by the mining process, forming relatively large expanses of nesting habitat used by both species. Modern mines store waste sand in limited quantities along the edge of the lake but also in piles away from the lake. Traditional mines also differ from modern mines in that they are routinely converted to housing developments with intermediate transition sites that host the largest number of nests for brief periods. Based on the previous 28 yr of decline, traditional mines and their productive derivatives are projected to continue to decline, thereby further reducing overall nesting habitat. Piping plovers and least terns are expected to nest in our study sites for the foreseeable future, but overall numbers are expected to be smaller than what has been observed in previous decades. Local declines in our study area will have local and regional implications for the recovery and management of these two species of conservation concern.

Key words: aggregate mining; endangered species; least terns; novel ecosystems; piping plovers.

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INTRODUCTION

The goal of recovering threatened and endangered species is to create conditions ensuring the long-term sustainability of populations without perpetual human intervention (Rohlf et al. 2014). Declines of many populations of species that become threatened or endangered are often due to the loss or alteration of natural habitats (Kerr and Deguise 2004, Venter et al. 2006). Endangered or threatened species rarely or infrequently occupy novel ecosystems—human-modified or engineered niches in the environment (Hobbs et al. 2006, Hallett et al. 2013). In situations in
which threatened or endangered species use or even rely on novel ecosystems, it is not only critically important to understand how these habitats influence populations, but also the patterns and processes that drive the distribution, availability, and persistence of the habitats themselves (Moreira et al. 2017, Planchuelo et al. 2019).

Along the Platte River and its tributaries in Nebraska (hereafter Platte River system), sand and gravel mines and their derivatives (i.e., lakeshore housing developments) are novel ecosystems that displace other natural (e.g., subirrigated prairie) or other human-created (e.g., agricultural fields) systems (Sidle and Kirsch 1993, Brown et al. 2011). Piping plovers (Charadrius melodus; hereafter, plovers) and Interior least terns (Sternula antillarum athalassos; hereafter, terns), two highly mobile and disturbance dependent bird species, readily colonize and breed at these sites because they provide nesting and foraging habitat. Plovers are listed as threatened by the federal Endangered Species Act (ESA; 7 U.S.C. § 136, 16 U.S.C. § 1531 et seq.) and Nebraska Nongame and Endangered Species Conservation Act (Nebraska Rev. Statute § 37-801-811) and terns are listed as endangered under the Nebraska state statute. Plovers and terns nest at these sites in areas of unvegetated or sparsely vegetated sand adjacent to water bodies created by the extraction of aggregate. This type of habitat is transitory and dependent on continual disturbance (Sidle and Kirsch 1993, Brown et al. 2011). Physical disturbance at these sites involves the dredging, processing, and the redistribution of aggregate. Without disturbance, such as when marketable aggregate is depleted and mining ceases, sites become vegetated and unsuitable for nesting (Sidle and Kirsch 1993).

Plovers and terns also nest and raise their young on natural sandbar habitats within the channel of the Platte River (Sidle et al. 1992, Jorgensen et al. 2012). The form and function of the Platte River have been altered since settlement by Euro-Americans by the direct and indirect consequences of dams, water diversions, and bank stabilizations (Williams 1978, Johnson 1994, Joeckel and Henebry 2008). Consequently, the contemporary distribution of plovers and terns on natural habitats has been reduced compared to historical periods (Sidle et al. 1992, Kirsch 1996; Alexander et al., unpublished manuscript). The presence and availability of sand and gravel mines and the concurrent decline of riverine habitats over time have resulted in a redistribution of the species within the Platte River system (Sidle et al. 1992, Kirsch 1996). In fact, a majority of nesting in recent decades in the Platte River system by both species has occurred on off-river sites and not on in-channel riverine habitats (Brown et al. 2017, 2018, Farrell et al. 2018).

The role of mines and their derivatives (hereafter off-river sites) in the management and recovery of these two species in the Platte River valley has been studied and debated by researchers and policymakers for decades. Habitats, food resources, and demographic consequences (e.g., nest fates, depredation rates) are different between off-river and in-channel habitats (Kirsch 1996, National Research Council 2005, Sherfy et al. 2012b). In the past, off-river sites have been viewed as deficient and unable to sustain populations of both species when compared to in-channel habitats created and maintained by river flows and sediment deposition on altered, albeit functional, stretches of river (National Research Council 2005). Habitat produced by natural processes has been shown to be in some ways superior to managed habitats (Hunt et al. 2018, Nefas et al. 2018, Walker et al. 2019, Robinson 2020). Arguably, off-river sites cannot serve as substitutes for natural habitats because they are not self-sustaining systems, as they require perpetual investment of capital to be maintained in a plagioclimax state (sensu Morris 1981) and provide little benefit to other at-risk species dependent on riverine habitats (National Research Council 2005). However, human-created habitats play an important role in supporting populations of both species in the Great Plains. Recent research (Catlin et al. 2016, Zeigler et al. 2017) focused on plovers shows off-river sites that provide stable sources of nesting habitat in the lower Platte River system, even when not intensively managed specifically for the species, not only support local numbers, but also augment regional populations.

Because of the potential importance of off-river sites, a relevant question that has not been addressed is whether or not the industry that has incidentally produced these novel ecosystems will continue to do so into the future. This is especially pertinent because loss of breeding...
habitat was a primary reason both species were listed (U.S. Fish and Wildlife Service 1988, 1990). Habitat availability at off-river sites has been relatively stable since the late 1970s and mid-1980s (Sidle and Kirsch 1993), which corresponds to the period when both species were state and federally listed. However, industries are rarely static, particularly industries influenced by multiple economic factors. Changes or trends in the presence and availability of off-river sites and habitats will have consequences for these populations, as well as the management and recovery of plovers and terns in the Platte River system and the Great Plains. The purpose of this study was to (1) evaluate how the number, size, and spatial distribution of different types of off-river sites hosting different numbers of nesting plovers and terns have changed over time, (2) determine how current trends in the number of different site types will affect future habitat, and (3) assess how changes in site types have and may have on these two species that use these habitats.

METHODS

Study area and study systems

We refer to our study area as the lower Platte River system (LPRS) which included the lower Platte, lower Loup, and lower Elkhorn river valleys in eastern Nebraska (Fig. 1). The lower Platte River portion extends 166 km from the confluence of the Loup and Platte rivers downstream to the confluence of the Platte and

Fig. 1. Lower Platte River system study area (light gray shading) examining nesting in novel ecosystems by Piping Plovers and Least Terns in east-central Nebraska. Off-river sites shown were those active during the period of study, 1993–2020.
Missouri rivers. The lower Loup River portion of the LPRS extends 45 km from Genoa, Nebraska downstream to the confluence of the Platte and Loup rivers. The lower Elkhorn River portion extends 129 km from West Point, Nebraska down to the confluence of the Platte and Elkhorn rivers. Although numbers are variable from year to year, the LPRS generally hosts the majority of nesting terns and as much as 40% of the nesting plovers in the entire Platte River system (Lott 2006, Elliott-Smith et al. 2015). A large portion of the state’s human population also lives within 50 km of downstream portions of the lower Platte River (Archer et al. 2017). This includes the state’s two largest cities, Omaha and Lincoln, which are both major economic centers (Archer et al. 2017). Off-river sites are distributed throughout the entire Platte River system but are usually located near population centers.

**Study species**

Plovers are migratory shorebirds that place their nest and eggs directly on sandy or gravelly substrate near water (Elliott-Smith and Haig 2020). Three different populations inhabit North America and breed along the Atlantic Coast, Great Lakes, and Great Plains, respectively (Elliott-Smith and Haig 2020). Plovers winter along the southern Atlantic and Gulf coasts as well as the Caribbean (Elliott-Smith and Haig 2020). Plovers primarily feed on invertebrates gleaned from various substrates along the shorelines of waterbodies (Elliott-Smith and Haig 2020).

Terns are migratory colonial nesters that also place their nest and eggs directly on the ground (Thompson et al. 2020). The species breeds along Atlantic, Gulf, and southern Pacific coasts of North America as well as along major rivers of the midcontinent (Thompson et al. 2020). Terns winter off eastern coasts of Mexico, Central and South America (Thompson et al. 2020). Terns primarily feed on small fishes, which they locate by flying and hovering over water and then capture by plunge diving into the water (Thompson et al. 2020).

The Interior population of the tern was federally listed as endangered in 1985 (50 FR 21784-21792), and the plovers were federally listed as threatened in 1986 (50 FR 50720-50726). Prior to federal listing, the tern was state-listed as threatened in Nebraska in 1976 because of habitat loss (Lock 1977). The tern was federally delisted in February 2021 for various reasons, including population increases in parts of the species’ range (86 FR 2564-2581). Plovers and terns nest in mixed-species aggregations in the Platte River systems (Farrell et al. 2018, Brown et al. 2019). The Nebraska Game and Parks Commission and the Tern and Plover Conservation Partnership have monitored both species in the LPRS since the mid-1980s.

**Site classification**

Off-river sites in the LPRS are typically initially created by the mining industry (Burchett 1990). Mine site locations are selected based on the presence of accessible and useable sand and gravel deposits and proximity and access to markets where product is sold (Burchett 1990, Pit and Quarry 2016). Both conditions exist in the Platte River system (Burchett 1990, Burchett and Eversoll 1990). Mine sites are usually located adjacent to or within 1 km from river channels and less often up to 4 km from river channels. Thus, new habitat patches created by the industry are in close proximity to existing habitat and are readily found by both species. Sand and gravel are mined in moist or wet conditions by open-pit excavation and dredging (Burchett 1990). This mining process generally involves clearing of vegetation and removal of unmarketable soil (overburden), extracting aggregate using heavy equipment, and processing the extracted product. Mine sites are generally characterized by the presence of various equipment used in the industrial process, different piles of extracted aggregate, and a lake created by the dredging process. Material is typically sold and transported away from the mine site while some proportion remains on site as waste sand (U.S. Geological Survey 2018). Areas of waste sand usually serve as plover and tern nesting sites. The lifespan of any one mine site is limited based on the amount of marketable and reclaimable aggregate available at the site. Sites are often converted to other uses once mining ceases, including recreation areas, lakeshore housing developments (Brown et al. 2018), and in some cases directly to managed tern and plover nesting areas (Farrell et al. 2018). The mechanical disturbance required to convert a sand and gravel
mine into a lakeshore housing development usually extends the span of time in which a site provides habitat appropriate for nesting plovers and terns.

We used aerial imagery, information from regular site visits and discussions with site owners and managers to classify off-river sites in the LPRS for each year from 1993 to 2020. We categorized all off-river sites based on their site characteristics (e.g., presence or absence of mining equipment or houses), purpose and use into six distinct site types: (1) active traditional open-pit mines, (2) active modern open-pit mines, (3) abandoned/inactive mines, (4) transition sites, (5) lakeshore housing developments, and (6) defunct sites (Fig. 2). Active traditional open-pit mines (traditional mines) and active modern open-pit mines (modern mines) are both sandpit types actively mined by a sand and gravel mining company and regulated by the federal Mine Safety and Health Administration (MSHA). The difference between these two types of sand and gravel mines is primarily how waste sand is stored. Traditional mines store waste sand in spoil piles or plumes along the edge of the lake, forming large expanses of sandy shorelines. Modern mines store waste sand in limited quantities along the edge of the lake but also in piles away from the lake. Waste sand is generally stored for short periods before it is disposed; thus, the amount of sandy shoreline on a given site is less than at a traditional mine.

Abandoned or inactive mines are no longer actively mined or regulated by MSHA. These mines have been taken out of production but have not been reclaimed or vegetated. Transition sites are off-river sites that are being converted from a mine to a housing development. The sites are no longer managed by a sand and gravel mining company and do not have homeowners in residence on the property. During the transition period, sites are reconfigured as aggregate is redistributed; large areas are disturbed to make the sites suitable for housing. Lakeshore housing developments (housing developments) are off-river sites managed by a homeowners association and/or developer, with at least one house having homeowners in residence on the property. Some proportion of housing development are open areas of sand without houses, and these areas provide nesting habitat. Defunct sites no longer provide habitat and do not support nesting plovers or terns. This occurs when an inactive site no long provides habitat because it has become too vegetated, or when a housing development has numerous structures, residents, and vegetation whereby nesting habitat of sufficient area to support nesting is no longer present.

We used Google Earth (Google 2020) to view historical aerial imagery, as well as information from site visits, to count the total number of off-river sites with nesting habitat within the LPRS each year from 1993 to 2020 for all sites combined and for each distinct site type. We used aerial imagery and ArcGIS (ESRI 2018) at a 1:20,000 scale to determine the size of each off-river site; the total area of these sites includes all possible nesting areas (sand, spoil piles, undeveloped edge), open water, and any developed footprint such as buildings, housing, or locations with large stationary equipment. Property boundaries were typically readily apparent on aerial photos because sites were bordered by dense vegetation, roads, structures, or agricultural fields. Site visits were also used to supplement information from aerial photographs. We chose to measure the overall area of a site, rather than identifying specific areas of a site as nesting habitat, for the following reasons: (1) distinguishing all habitat from non-habitat is difficult from aerial images; (2) sites are perpetually changing and aerial photographs from any one time may not represent conditions during a nesting season; (3) some limited areas of sand are managed to be unsuitable in some years by regular raking or by using Mylar flagging to deter birds from nesting in those areas (Marcus et al. 2007); and (4) birds occasionally nest in unusual places (e.g., along roads, parking lots) at these sites. Other than limited site modifications directing plovers and terns to nest in certain areas and avoid other areas, habitat at off-river sites in the LPRS are not managed specifically for plovers and terns.

**Evaluation of bird use by site type**

From 2008 to 2020, the Tern and Plover Conservation Partnership monitored a subset of all off-river sites within the LPRS in which their personnel were allowed to access and recorded the nesting activity of terns and plovers through the
duration of the breeding season (typically late April through early August; see Brown et al. 2017, 2018 for overview of methods). The number of sites monitored ranged from 18 (2008) to 28 (2013), and in most years, at least one of each of the five site types was monitored.

Fig. 2. Different site types with example imagery and possible transition pathways within the lower Platte River system. Traditional mines store waste sand in spoil piles or plumes along the edge of lake created by the mining process, forming relatively large expanses of sandy shorelines that is used as nesting habitat by both species. Modern mines store waste sand in limited quantities along the edge of the lake but also in piles away from the lake. Traditional mines also differ from modern mines in that they are routinely converted to housing developments with intermediate transition sites. Modern mines were not observed being converted to housing developments during the period 1993–2020. Aerial imagery is included for modern mines for visual comparison to other site types. Site imagery from Google Earth (Google 2020).
throughout the breeding season. We compared the number of nests by site type to determine if different off-river site types support different numbers of nests. We chose number of nests because this measurement was collected consistently across our sites during the study period; counts of adults or pairs were not. Even though number of nests may include some proportion of re-nests, we believe it is an informative metric about bird use at sites. We did not monitor an equal number of off-river sites within each type on a given year. We therefore standardized our nesting data by the number of a given site type monitored per year. We compared the number of nests by site type using a one-way ANOVA and determined significance between groups using the non-parametric Games-Howell post hoc test. We compared plover nests at each site type and tern nests at each site type separately for nesting analysis.

**Lifespan of off-river sites**

We used a multi-state modeling approach to estimate the lifespan and transition probabilities of traditional mines in the LPRS. We treated traditional mines and multiple derivative site types as different states and used a Markov modeling approach to estimate transition probabilities from one site type to the next (Callaway and Davis 1993). Our study was suited for this type of analysis as the site types are both discrete states and have differing impacts on the species of interest (Usher 1979, Breininger et al. 2010). Previous studies on avian species of conservation concern have implemented multi-state models to assess the dynamics of shifting habitats and determine potential impacts on various aspects of species’ life histories (Brown et al. 2003, Breininger et al. 2010, Duarte et al. 2016). While our system also features species of concern in a dynamic mosaic of habitats, we only modeled the habitat transitions and not the survival, occupancy, or productivity of our species of interest within those habitats. We classified all sites to a given type (i.e., no missing states), and because we assigned site classifications by year, we estimated transition probabilities on an annual timescale. We defined five possible states in our system and six possible transitions between states: All sites in this analysis began as an active traditional mine. Possible transitions from this state include becoming an inactive mine site (transition 1) or a transition site (transition 2). Inactive sites can become transition sites (transition 3) or become defunct (transition 4). All transition sites by definition become housing developments (transition 5). The last possible transition is a housing development to defunct (transition 6, Fig. 2). The final state in our system is a defunct site, which we defined as a site that no longer provides nesting habitat and does not support nesting terns or plovers. There is no transition from a defunct site, and none of the possible states can revert to other previous states in our system (Fig. 2). We only modeled transition probabilities for traditional mines and not modern mines in our system. Modern mines have not been observed changing into other states in our system and become defunct soon after they are abandoned.

We included two site-specific covariates to our models that might influence the transition probabilities between states. These were the location of a site based on river mile and the site size. Generally, the further upriver a site is located on the Platte, the farther away it is from the major population centers in eastern Nebraska (specifically Omaha). We predicted this would influence the attractiveness of a mine for potential development into residences, with mines closer to Omaha being most likely to become housing developments. We also predicted that the size of a mine influences the feasibility and potential housing density. We predicted larger mines offer more space for development, which in turn potentially make a site more profitable (larger developments accommodate more houses).

We considered models with both covariates on most possible transitions in our system to determine if size or position along the Platte would significantly influence the transition probabilities throughout the lifespan of a traditional mine and its derivatives. We did not consider models with covariate effects on the transition from an inactive mine to a transition site (transition 3), as this was a relatively rare occurrence in our system. We tested the most general model using median $\hat{c}$ and found no evidence for overdispersion ($\hat{c} < 1.0$, Breininger et al. 2009, Converse et al. 2009). We compared models using corrected Akaike’s information criterion (AICc; Akaike 1974). We used the highest-ranking model.
(lowest AIC<sub>c</sub>) to project the possible states and transitions for the remaining 11 traditional mines (as of 2020) in the LPRS over a 25-yr period (i.e., 2020–2045). We used Program R (R Core Team 2019) for all statistical analyses and the msm and mstate packages (de Wreede et al. 2011, Jackson 2011) for modeling transition probabilities and future projections.

**RESULTS**

From 1993 to 2020, the number of off-river sites and the overall available area within the LPRS peaked in 1994 and 1995 with 52 available sites totaling over 3909 ha. The lowest number of sites and total available area occurred in 2019 and 2020, with 32 sites totaling 2508 ha (Fig. 3).

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**Fig. 3.** (A) Total area of off-river nesting sites for piping plovers and least terns by mine type in the lower Platte River system from 1993 to 2020. (B) Total number of traditional mines (black squares), modern mines (gray circles), and traditional mine derivatives (blue triangles; inactive mines, housing developments, and transition sites) by year from 1993 to 2020.
The number of active traditional mines peaked in 1997 and 1998 at 33 sites and declined steadily to a low of 11 active traditional mines in 2020. There was one modern mine in the LPRS in 1994, and this increased to 10 active modern mines by 2020. The number of transition sites, inactive/abandoned mines, and housing developments fluctuated between years with no apparent trend (Fig. 3).

**Tern and plover nesting**

We recorded an average of 46 (standard error = ±5.3; range 16–77) plover nests and an average of 171 (±22.2; range 16–290) tern nests per year in LPRS. We recorded 1.8 (±0.2) plover nests per site monitored and 6.8 (±0.9) tern nests per site monitored. The number of plover nests per site per year differed ($F_{4,53} = 24.93$, $P < 0.001$, Fig. 4) between site types and was highest at housing developments (5.4 ± 0.4; range = 3–8.7), and transition sites (4.8 ± 1.3; range = 0–9.3), followed by traditional mines (1.5 ± 0.2; range = 0.6–2.5), modern mines (0.9 ± 0.3; range = 0–4), and inactive mines (0.6 ± 0.2; 0–2.5). Nest numbers at housing developments differed ($P < 0.001$) from all other sites except transition sites ($P = 0.90$). The average number of tern nests per site per year also differed ($F_{4,53} = 12.71$, $P < 0.001$, Fig. 4) between site types and was highest at transition sites (21.6 ± 6.4; range = 0–46). After transition sites, tern nests were most numerous at housing developments (11.2 ± 1.6; range = 2.5–19.8), followed by traditional mines (7.7 ± 1.2; range = 0.7–13.2), modern mines (2.8 ± 0.7; range = 0–7), and inactive sites (1.2 ± 0.5; range = 0–6). Inactive mines had marginally fewer ($P = 0.094$) nests than modern mines and fewer ($P < 0.002$) tern nests than all other site types, and traditional mines had more ($P = 0.013$) tern nests than modern mines.

Fig. 4. Number of piping plover (gray) and least tern (gold) nests per site monitored in the lower Platte River system 1993–2020. The horizontal line at the waist of the box is the median. The bottom and top of the box show the 25th and 75th percentiles, respectively. The extent of the vertical lines (whiskers) shows either the maximum value or the value 1.5 times the interquartile range of the data, whichever is smaller.
Lifespan of traditional mines and derivatives

We did not observe any modern mines converted to transition sites or housing developments. We documented a total of 14 modern mines within 28 yr, four of which were defunct by 2020. All other possible states for a mine (inactive, transition site, housing development) originated from traditional mines. Twenty-two (50%) of 44 traditional mines became inactive before any other state. Eleven (25%) traditional mines became transition sites. Eleven (25%) of the traditional mines we monitored remained active mines. The majority of the 22 inactive sites (n = 18, 82%) became defunct, with three (14%) remaining as inactive sites and one (5%) become a transition site for later development. All 12 sites that at one point were transition sites became housing developments. Of the 12 housing developments, 8 (67%) became defunct by 2020. Transition sites had an average lifespan of 2.4 yr (range 1–6 yr) before becoming housing developments. Housing development average lifespan was 9.2 yr (range 3–23 yr) in our system, and inactive sites that did not become transition sites had an average lifespan of 4.4 yr (range 3–12 yr) before becoming defunct.

The highest-ranking model for traditional mine site transitions was the model including site size at initial transition from an active mine to an inactive mine (Table 1). The null model was <2 AICc from the highest-ranking model and had only a marginally lower Akaike weight (0.28 vs. 0.40). Contrary to our predictions, increasing size decreased transition probabilities from active traditional mines to inactive mines in our system. However, the influence of site size on mine transitions was likely negligible given the coefficient was small (β = −0.007 ± 0.004) and the closeness of this model to the null model by AICc. The highest transition probability between different states in our system was from transition site to housing development (ΨTrHs = 0.428, Table 2), further reflecting the relatively short lifespan of transition sites in the LPRS.

Projected state transitions for remaining traditional mines

We used the highest ranked model including size at transition from active to inactive mine to project possible states for the remaining 11 active traditional mines in our study area over the next 25 yr. Overall, the probability that a current mine remains an active mine after 25 yr is low (−x = 0.16, range = 0.08–0.33), whereas the highest probable state after 25 yr is defunct and thus unsuitable for nesting by terns and plovers (−x = 0.61, range = 0.38–0.72, Fig. 5). The time at which a current mine was projected to have the highest probability of becoming a transition site is at 9 yr (0.08–0.1) and peaks again at 23–24 yr (−x = 0.11, range = 0.08–0.16). Transition sites will become housing developments and can either remain housing developments or become defunct. The probability that a current active traditional mine in 2020 was either an

Table 1. Top model (AICc = 518.7) and candidate models with AICc scores for traditional mine state transitions for nesting piping plovers and least terns in eastern Nebraska.

| Model | ΔAICc | wi |
|-------|-------|----|
| Size1 | 0.0   | 0.40 |
| Null  | 0.6   | 0.28 |
| Size1 + river mile1 | 2.3 | 0.13 |
| River mile1 | 2.4 | 0.12 |
| Size1,2,4 + river mile1,2,4 | 3.7 | 0.06 |
| Size1,2,4,5,6 | 8.3 | <0.01 |
| River mile1,2,4,5,6 | 12.1 | <0.001 |

Notes: AICc, corrected Akaike’s information criterion. Superscripts (1,2,4,5,6) denote covariate at the corresponding transition (1, mine to inactive; 2, mine to transition; 4, inactive to defunct; 5, transition to house; 6, house to defunct).

Table 2. Estimated transition probabilities for traditional sand and gravel mines in the lower Platte River system from 1993 to 2020 based on the top multi-state model.

| Transition | Estimate | CI          |
|------------|----------|-------------|
| ΨTmIn     | 0.950    | 0.928–0.964 |
| ΨTmHs     | 0.033    | 0.021–0.052 |
| ΨTmTr     | 0.017    | 0.009–0.031 |
| ΨInIn     | 0.793    | 0.707–0.878 |
| ΨInHs     | 0.011    | 0.001–0.072 |
| ΨInTr     | 0.196    | 0.123–0.310 |
| ΨTrTr     | 0.572    | 0.249–0.766 |
| ΨTrHs     | 0.428    | 0.243–0.751 |
| ΨHsHs     | 0.900    | 0.801–0.950 |
| ΨHsDf     | 0.100    | 0.049–0.198 |

Notes: CI, confidence interval. Transition probabilities for states that remained the same were estimated by subtraction. Superscript labels are as follows: Tm, traditional mine; In, inactive mine; Tr, transition site; Hs, housing development; Df, defunct site.
inactive mine or a housing development that can still support nesting plovers and terns after 25 yr was low (<0.20, Fig. 5).

**DISCUSSION**

Our results show industry practices that once were responsible for creating plover and tern habitat are changing, resulting in a decline in off-river nesting area and sites in the LPRS. Most important is the decline of traditional mine sites, which has two important consequences. First, traditional mines have hosted large numbers of both species compared to modern mines. Second, traditional mines also continue to provide nesting habitat when they are reconfigured as transition sites and ultimately transformed into housing developments. Transition sites and housing developments have hosted the largest numbers of nesting plovers and terns, albeit for brief periods of generally less than three and ten years, respectively. The observed low transition probabilities from a traditional mine to a transition site since 1993 along with the predicted low probability of remaining transition sites over the next 25 yr suggests that the availability of both housing developments and transition sites will be limited in the future. Given the relatively brief observed lifespans of transition sites (2.4 yr) and housing developments as suitable nesting sites (9.2 yr), we also expect limited availability of plover and tern nesting habitat from derivative site types that remain after the next 25 yr. The long-term decline in traditional mines portends future declines in transition sites and housing developments. This point is reinforced because we have not observed modern mines, which are essentially replacing traditional mines, being converted to housing developments in the LPRS.

Plover and tern nest counts observed at off-river sites have been different, and therefore, a reduction in habitat will have different impacts on the two species. Terns are colonial and nest in groups in relatively small areas. On average, nearly three times as many terns than plovers have nested at our study sites and a larger proportion of all terns in the LPRS have nested on in-channel habitats compared to plovers (Brown and Jorgensen 2009). Tern numbers observed at off-river sites have also been more variable from year to year as individual birds select between or respond to the availability or lack of habitat in

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**Fig. 5.** Projected state occupancy probabilities for the 11 remaining active traditional mines in eastern Nebraska from current year (2020, year 0) to year 25 (2045). Different colors correspond to individual mines.
the river channel. In years when high river flows inundate sandbars, we generally observe larger numbers of terns at off-river sites compared to years when inundation events do not occur (Brown and Jorgensen 2009, Brown et al. 2017, 2018). Thus, the availability of a single or a few sites during individual years can result in a marked shift in numbers. For example, in 2019 a record low 16 tern nests were observed at off-river sites in our study area. The following year, a total of 101 nests were observed, but nearly half (48) of those tern nests were at a single transition site not available in previous years. By contrast, plovers are territorial (Elliott-Smith and Haig 2020) and nest success and chick survival are negatively related to nesting density (Catlin 2009, Hunt et al. 2018). Reduction in off-river habitat is expected to result in lower numbers or higher densities of plovers, or both, which is expected to have adverse consequences on local populations.

Our study focused on coarse scale metrics of site type, overall site area and nest numbers to evaluate and predict how industries have and are expected to affect two species of concern. Future research should assess how industry practices and management of different site types influences the presence, absence, or amount of specific habitat features and how these finer scale habitat metrics affect habitat selection, use, and the various demographic consequences of such decisions by individual animals. Similar research (Sherfy et al. 2012a, Farrell et al. 2018) has been done at other off-river sites specifically managed for plovers and terns. This additional research in our system would provide a more complete understanding of how off-river sites in the LPRS affect or could affect local and regional populations. Those findings may also identify opportunities to work with industries to increase areas of usable habitat, extend the lifespan of these sites as it relates to plovers and terns or improve individual reproductive success. However, whether resources should be invested in these efforts hinges on whether such actions are or should be components of species’ overall recovery plans or strategies.

A reduction in off-river habitat in our study area is expected to negatively impact not only local numbers, but regional populations as well. Plovers and terns nesting on and along the Platte and Niobrara rivers, as well as the Missouri River along the Nebraska–South Dakota border, act as sub-populations within the broader interior ranges of the species (Lott et al. 2013, McGowan et al. 2014). Sub-populations in this region demonstrate metapopulation dynamics. Plovers in our study area regularly disperse to and from nesting areas along portions of the Missouri and Niobrara rivers on and near the Nebraska–South Dakota border (Hunt et al. 2015, Catlin et al. 2016, Zeigler et al. 2017), and the central Platte River and other breeding areas farther away (Brown et al. 2019). Limited banding data also suggests terns regularly disperse and colonize sites in a similar manner (Lingle 1993; NGPC, unpublished data). Plover metapopulation persistence in this region depends on off-river and other human-created habitats that provide a small but reliable source of nesting habitat and dispersers over time (Catlin et al. 2016).

The region in which the sub-populations occur is composed of a patchwork of de facto management units that a result of individual federal actions and efforts by entities to comply with the ESA. A consequence is a disproportionate allocation of resources among the different the management units. Along the Missouri River, the U.S. Army Corps of Engineers has spent considerable resources creating and managing habitats to benefit the species and to comply with a U.S. Fish and Wildlife Service Biological Opinion (U.S. Fish and Wildlife Service 2000). Similarly, the Platte River Recovery Implementation Program has allocated considerable resources along a 145 km portion of the central Platte River to manage 54 ha of nesting habitat in order to comply with the ESA (U.S. Fish and Wildlife Service 2006). However, in our study area, no program or controlling authority exists to create or maintain habitats. The local and regional benefits that off-river sites in LPRS have provided to plovers and terns over several decades have been a by-product of industrial and commercial processes. Habitat creation and maintenance have occurred with no planning and essentially no cost to government agencies and conservation organizations. Industry, government agencies, and the University of Nebraska-Lincoln formed the Tern and Plover Conservation Partnership in 1999. This partnership implements limited management efforts and works with private entities primarily to avoid ESA violations (take of adults, nests, and young; Brown et al. 2011). This partnership is
partially funded by industry and even though it is a successful model of endangered species conservation on private lands (Brown et al. 2011), its current capacity to affect the amount and quality of habitat produced by industries is limited.

Plovers and tern populations in the Great Plains presently exist in and respond to a shifting mosaic of habitats produced by an array processes occurring at different rates and time intervals within native and novel ecosystems (McCauley et al. 2016; Alexander et al., unpublished manuscript). Natural and human-created habitats are a product of different processes, but habitat produced by both have played important roles in supporting plover and tern populations. Even though industrial and commercial activities have incidentally created large amounts of habitat in the past, our analysis does not support any notion off-river sites will permanently replace declining natural habitats serendipitously through industry practices. If not incidentally produced by industry, off-river sites only remain permanently viable through perpetual intervention, which are mostly dependent on federal government appropriations. Furthermore, perpetuation of off-river sites only maintains numbers of both species rather than building population resilience because the habitats themselves are not resilient. This approach is a consequence of how the ESA is structured and has been criticized (Gunderson 2013). Although there are ecological and societal trade-offs in how resources are used, natural habitats have the advantage of being self-sustaining and, in many ways, are superior to artificial habitats (Hunt et al. 2018, Nefas et al. 2018). Nonetheless, additional loss of off-river sites and habitat will only present further challenges because limited habitat is a primary reason these species were originally listed and why they remain conservation priorities. These challenges will be further compounded if natural habitat continues to be or becomes further reduced or impaired.

Policy- and decision-makers must consider the shifting habitat dynamics for these two threatened and endangered species that rely on disturbance-mediated systems in order to implement effective and adaptable management strategies that optimize outcomes. Our results, along with other studies (McCauley et al. 2016; Alexander et al., unpublished manuscript), provide the basis and opportunity to evaluate changes and directional trends in habitat and how future habitat conditions will affect these two species. This and other information should be proactively used when considering what investments and actions should be undertaken at the present time to maintain species’ numbers, but more importantly, which investments and actions will be most beneficial to provide a sustainable recovery for both species in the future.

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