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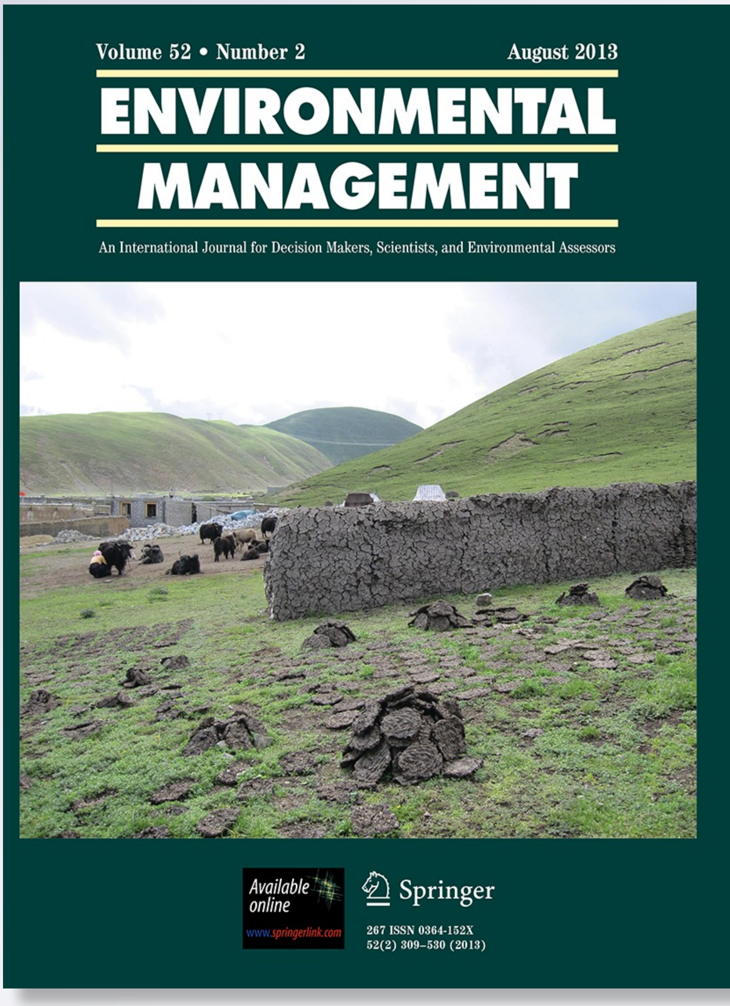

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Abstract Populations of many shorebird species are declining; habitat loss and degradation are among the leading causes for these declines. Shorebirds use a variety of habitats along interior migratory routes including managed moist soil units, natural wetlands, sandbars, and agricultural lands such as harvested rice fields. Less well known is shorebird use of freshwater aquaculture facilities, such as commercial cat- and crayfish ponds. We compared shorebird habitat use at drained aquaculture ponds, moist soil units, agricultural areas, sandbars and other natural habitat, and a sewage treatment facility in the in the lower Mississippi River Alluvial Valley (LMAV) during autumn 2009. Six species: Least Sandpiper (*Calidris minutilla*), Killdeer (*Charadrius vociferous*), Semipalmated Sandpiper (*Calidris pusilla*), Pectoral Sandpiper (*C. melanotos*), Black-necked Stilt (*Himantopus himantopus*), and Lesser Yellowlegs (*Tringa flavipes*), accounted for 92 % of the 31,165 individuals observed. Sewage settling lagoons (83.4, 95 % confidence interval [CI] 25.3–141.5 birds/ha), drained aquaculture ponds (33.5, 95 % CI 22.4–44.6 birds/ha), and managed moist soil units on public lands (15.7, CI 11.2–20.3 birds/ha) had the highest estimated densities of shorebirds. The estimated 1,100 ha of drained aquaculture ponds available during autumn 2009 provided over half of the estimated requirement of 2,000 ha by the LMAV Joint Venture working group. However, because of the decline in the aquaculture industry, autumn shorebird habitats in the LMAV may be limited in the near future. Recognition of the current aquaculture habitat trends will be important to the future management activities of federal and state agencies. Should these aquaculture habitat trends continue, there may be a need for wildlife biologists to investigate other habitats that can be managed to offset the current and expected loss of aquaculture acreages. This study illustrates the potential for freshwater aquaculture to provide habitat for a taxa at risk. With the rapid growth of aquaculture worldwide, the practices of this industry deserve attention to identify benefits as well as risks to wildlife.

Keywords Agricultural wetlands · Aquaculture · Lower Mississippi Alluvial Valley · Migration · Shorebirds

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Introduction

Many populations of shorebird species are thought to be declining with negative population trends outnumbering increasing trends by 42–2 (Morrison and others 2006). Shorebird species in suspected decline include many that migrate through the continental interior of North America; interior-migrating shorebirds are declining at much higher rates than coastal migrants (Thomas and others 2006a). Much of the habitat in the interior region is ephemeral and dependent on water availability. Unlike coastal migrants, interior shorebird migrant habitat use is variable from year to year (Skagen 1997; Skagen and others 2008). This variability in habitat availability may explain why shorebirds within the interior are known to colonize habitat quickly, often within 24 h after it becomes available (Skagen and Knopf 1994).

Many of these interior-migrating shorebird species pass through the lower Mississippi River Alluvial Valley (LMAV) as they move between their breeding and non-breeding grounds (Ranalli 2012). The LMAV is an agricultural region with 45 % of the area in row crops (Butcher and others 2007), such as soybeans, rice, cotton, and sorghum. Shorebirds, including Killdeer (*Charadrius vociferous*), Wilson's Snipe (*Gallinago delicata*), and Buff-breasted Sandpiper (*Tryngites subruficollis*), use agricultural fields as foraging habitat, particularly during the non-breeding season (Fredrickson and Taylor 1982; Hands and others 1991; Colwell 2010). However, soybean and rice fields provide potential shorebird habitat during the autumn and winter only after they are harvested and subsequently flooded. In the LMAV, these crops are harvested between early September and late October (USDA National Agricultural Statistics Service 1997) but not typically flooded until after 1 November (Twedt and others 1998). Hence, when migrating shorebirds are passing through the LMAV from mid July through early October most of these agricultural habitats are not suitable for shorebirds (Twedt and others 1998).

Aquaculture has the potential to provide habitat to shorebirds earlier in the fall when flooded agricultural fields are not yet available. Aquaculture can provide mudflat and shallow water habitat for shorebirds (Huner and Musumeche 1999; Elliot and McKnight 2000; Loesch and others 2000; Huner 2009) via ponds drawn down for maintenance. Although aquaculture has been traditionally seen as being in conflict with shorebirds and other wildlife (e.g., Schaeffer-Novelli and others 2006; Gibbs 2007), shorebirds in the LMAV have been positively associated with freshwater aquaculture facilities. Shorebirds have been documented using crayfish impoundments in Louisiana (Huner and Musumeche 1999; Huner 2009) and the U.S. Fish and Wildlife Service estimated that as many as 531,000 shorebirds used drained aquaculture ponds during autumn migration in 1995 and 1996 (Elliott and McKnight 2000). However, to date no comparison has been made of the use of aquaculture habitat relative to other shorebird habitat available within the LMAV.

The LMAV Joint Venture working group (Loesch and others 2000) estimated that 2,000 ha of shorebird habitat were needed to meet autumn migration shorebird forage needs. Much of that needed habitat was available as drained aquaculture ponds. In recent years, there has been a rapid contracting of the aquaculture industry in the region in response to increased feed prices and competition with imports from Asia (Streitfeld 2008). These declines have resulted in a decrease in the number of aquaculture facilities in production in the three states comprising most of the LMAV (Arkansas, Louisiana, and Mississippi) from a high of 64,000 ha in production in 2001 to only 25,000 ha in January of 2012 (USDA 2012; Fig. 1). The availability of shorebird habitat on aquaculture facilities is limited to those impoundments being drained for renovation, which is typically about 3 % of the total area in production (USDA 2012).

In addition to drained aquaculture ponds and seasonally flooded crop fields, shorebirds in the LMAV are known to frequent moist soil units on public lands, marshes, pond and river edges, and sandbars (Twedt and others 1998). Due to reduced water availability, shorebird habitat during autumn (July–September) is believed to be more limited than habitat during the spring (Elliot and McKnight 2000). The objectives of our study were to compare shorebird use among habitats during autumn migration in the LMAV.

Methods

Study Area

The study area encompassed the Alluvial Valley of the lower Mississippi River (Fig. 2a). The 99,957 km^2 LMAV represents the historic floodplain and valley of the lower Mississippi River and encompasses portions of Arkansas, Louisiana, and Mississippi and also contains small sections of Tennessee, Missouri, Illinois, and Kentucky. The dominant aquaculture products produced in the region are cat-(Mississippi and Arkansas), bait-(Arkansas), and crayfishes-(Louisiana; USDA National Agricultural Statistics Service 2006).

During 2009, we conducted surveys for shorebirds in the LMAV between 17 July and 24 September, a period that encompassed the peak migratory period for shorebirds in the LMAV (Twedt and others 1998). Surveys were

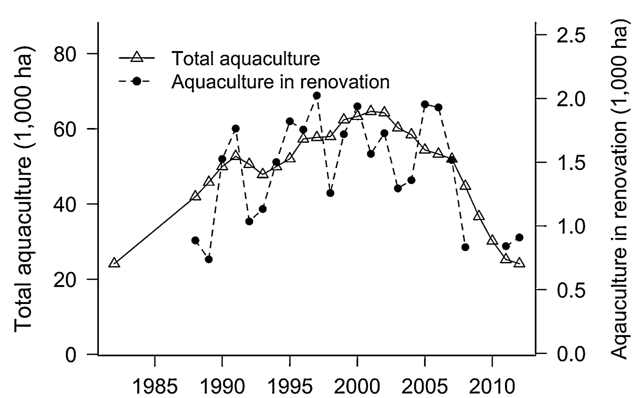

Fig. 1 The total water surface area in aquaculture production (*left y* axis) and in renovation (*right y* axis) in Arkansas, Louisiana, and Mississippi between 1982 and 2012 (*source* USDA National Agricultural Statistics Service 2012)

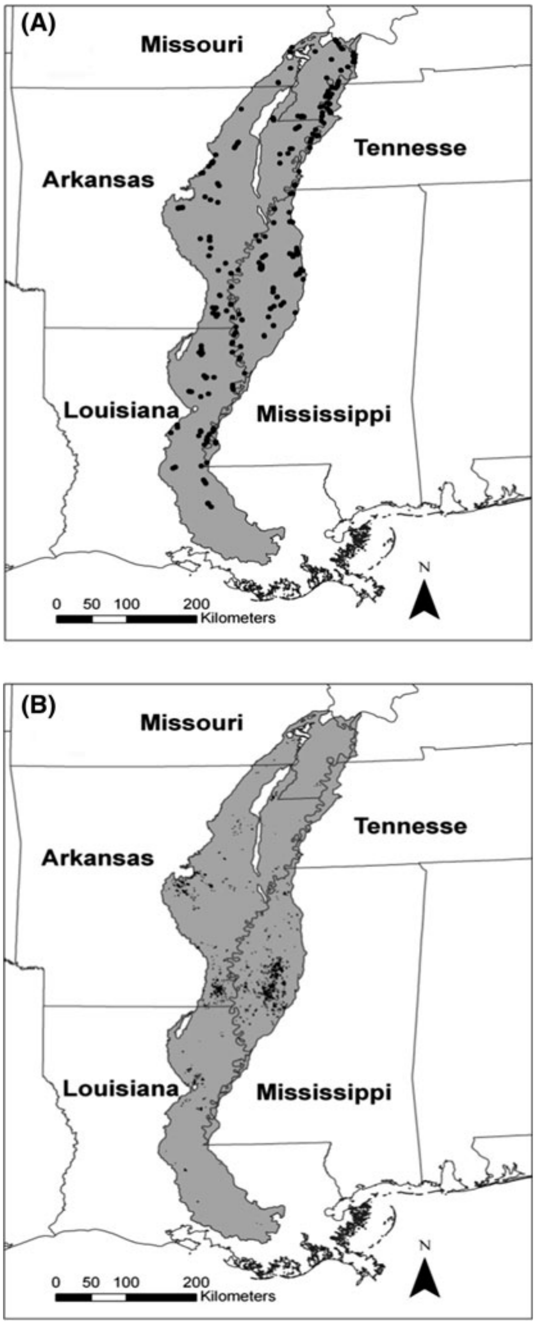

Fig. 2 **a** Survey locations used during autumn migration from 17 July to 24 September 2009 in the lower Mississippi River Alluvial Valley (LMAV, *shaded region*) and **b** distribution of aquaculture facilities in the LMAV as of 2002 (data courtesy of Ducks Unlimited)

stratified by land use: public managed moist soil units, aquaculture facilities, sandbars, borrow pits, and agriculture (Table 1). In addition, we surveyed one wastewater treatment plant, T. E. Maxson, commonly known as Ensley Bottoms, that is known to support high numbers of shorebirds during migration (DeCecco and others 1998). We surveyed all public lands that were known to be either actively managed for shorebirds in 2009 or whose management was known to create shorebird habitat as identified through review of historical data and through conversations with managers of public lands in the LMAV. Because public lands are managed for multiple purposes and because shorebird habitat is often best managed on a rotational schedule (Rundel and Fredrickson 1981), not all sites that provided habitat historically were managed for shorebirds during 2009. Public lands included in the 2009 surveys consisted of moist soil units on National Wildlife Refuges (NWRs), Wildlife Management Areas (WMAs), and Conservation Areas (CAs).

To determine shorebird use of aquaculture ponds, we randomly selected sixteen 6 × 6 km blocks containing aquaculture ponds in the LMAV. Individual aquaculture ponds were chosen using the generate random points tool in Hawth's Tools (Beyer 2004) in ArcGIS 9.1 (ESRI 2006) using a shapefile of aquaculture ponds in the LMAV during 2002 complied by Ducks Unlimited (Fig. 2b). Each cell had the same probability of being included in the random sample but included cells had to be a minimum of 6 km from the next closest included cell. For each pond, we placed a 6 × 6 km block centered on that pond and surveyed all ponds within that block. The 16 blocks comprised 19.5 % of the available aquaculture land in the LMAV in 2002. Because aquaculture facilities were privately owned, permission to survey the area was granted before the start of the field season when the owner of aquaculture facilities could be identified ahead of time; otherwise permission was obtained in the field by locating the main office of the facility. In only one instance was permission denied, in that case we surveyed an adjacent block to the south.

To determine shorebird use of agricultural land, we randomly selected ten townships in the LMAV. To minimize time spent surveying inappropriate habitat, we first excluded any townships from this sample that were less than 70 % agriculture using the Landuse and Land Cover 2001 database (Homer and others 2004) and ArcGIS 9.1 (ESRI 2006).

We also surveyed sandbars and borrow pits along the Mississippi River although these sites were not randomly selected due to the logistics of site access; only sandbars visible from public land and borrow pits and other flooded land adjacent to levee roads with public access were surveyed.

Surveys

Each pre-selected site was surveyed three times over the course of the season, with each site visited once every 23 days over a 10-week period. All surveys were conducted during daylight hours (0700–1900 CST). For each site, an aerial image (≤2 m resolution) was uploaded into

Table 1 Survey sites for shorebirds during autumn migration 2009 in the lower Mississippi River Alluvial Valley

Survey locations	Number of sites
Moist soil units on public land	
Askew WMA, MS	1
Bald Knob NWR, AR	1
Catahoula Lake, LA	1
Catahoula NWR, LA	1
Coldwater NWR, MS	1
Coon Island WMA, MO	1
Eagle Lake WMA, TN	1
Oakwood WMA, AR	1
Otter Slough CA, MO	1
Red River WMA, LA	1
Sherburne WMA, LA	1
St. Catherine Creek NWR, MS	1
Ten Mile Pond CA, MO	1
Yazoo NWR, MS	1
Wastewater treatment	
Ensley Bottoms (T. E. Maxson Wastewater Treatment Plant), TN	1
Aquaculture	
Randomly selected aquaculture blocks (6 × 6 km)	16
Incidentally encountered drained aquaculture ponds	25
Joe Hogan Fish Hatchery, AR	1
Agriculture	
Randomly selected agriculture townships	10
Incidentally encountered flooded agricultural fields	56
Sod	
Incidentally encountered sod farms	7
Sandbars	
Sandbars visible from shore	16
Borrow	
Flooded fields and borrow pits adjacent to levee	37
Riverbanks and ponds	
Incidentally encountered riverbanks and ponds	11
Miscellaneous sites	
Overflow pond, MO	1
Morganza spillway, LA	1

ArcPad (ESRI 2006) onto a MobileMapper TMCX data logger. At the beginning of each survey, the observer delineated shorebird habitat at the site by drawing polygons either directly over the aerial photo on the data logger or onto a printed map. For each polygon we recorded four habitat descriptors: habitat type (dry-, wet mudflats, shallow water [<10 cm], deep water [10–20 cm]), estimated % vegetative cover, mean vegetation height (cm), and surface smoothness (smooth: such as a mudflat, some bumps or mounds: such as most natural habitat, numerous bumps or mounds: such as a tilled field). Water depth was assessed visually using bird legs as a guide when shorebirds or wading birds were present (Davis and Smith 1998) and water categories were based on the maximum depth used by small and medium-sized shorebirds (<10 cm) and large shorebirds (10–20 cm). Shorebirds were located and identified to species using binoculars and 20–60× spotting scopes.

The survey technique for shorebirds depended on habitat type. When possible, we adjusted our counts for incomplete detection. However, borrow pits and sandbars were generally small, irregularly shaped habitats (<1 ha) with limited vegetation that were surrounded by habitats unsuitable for shorebirds. For drained aquaculture ponds, although some of these ponds had a large amount of shorebird habitat available (maximum observed 18 ha, mean 2 ha) the maximum distance at which shorebirds could be detected and identified to species with spotting scopes was still much greater than the maximum width of these habitats, making distance methods of estimating detectability unsuitable. Furthermore, these habitats generally lacked vegetative cover or other visual obstructions that could conceal shorebirds and thus made it likely that most birds on these habitats were detected. For drained aquaculture ponds, borrow pits, and sandbars, the probability of detection was assumed to be one and the trained observer proceeded by using the aerial photo as a guide and a laser rangefinder to determine distances, and recorded the locations of all individuals or same-species groups onto the map in the correct habitat polygon, recording all the locations for one species before proceeding to the next species. This approach created a "snapshot" for each species present at the site, minimizing the effect of movement into or out of the site during the survey. Duration of the survey varied by the amount of habitat and number of shorebirds present, but was sufficient to identify all shorebirds to species. All surveys were conducted by SEL and one technician trained in shorebird identification and survey techniques.

For surveys at moist soil units and agricultural areas, shorebird detection was almost certainly less than one and we used distance-based methods of accounting for incomplete detection. The habitat at most moist soil units on public lands was generally moderately to heavily vegetated and often expansive. Similarly, agricultural fields were both expansive and contained visual obstructions that made complete detection unlikely. Using distance-based approach in this case assumed that (1) shorebirds on the line were detected with certainty, (2) shorebirds were detected at their initial locations, (3) distance measurements were exact, and (4) the placement of line transects was random with respect to the locations of shorebirds (although shorebirds themselves were not required to be randomly located; Buckland and others 2001). We surveyed moist soil units and agricultural fields using line transects, using the levee (moist soil units) that bordered the shorebird habitat or county roads (agricultural surveys) as the line and recording individuals and groups of shorebirds as they were detected. For shorebirds to be considered as a group, they had to be within the same 5-m radius circle and within the same habitat polygon. Shorebird locations were recorded on the map, using a laser rangefinder to aid in determining correct placement and distance from the line.

The one exception to this moist soil survey technique was Catahoula Lake, a 12,000 ha wetland basin recognized as a Wetlands of International Importance (RAMSAR site) and believed to provide habitat for many shorebirds during migration (maximum daily count 25,402; Skagen and other 1999). Historically, the lake basin fills during late autumn and water levels typically remain high throughout June and then recede beginning in July, with about 6,000 ha of mudflats exposed by the first week of August (Wills 1971). Due to the changing lake boundaries with water level fluctuations and lack of road access, levee-based line surveys were not an option with this site so we surveyed this area using three point counts set at the intersection of mudflat and shallow water habitat, with each point placed at least 800 m from the next closest point. Points were lined up on the eastern side of the lake, adjacent to Catahoula NWR and Dewey Wills WMA land. Because we were restricted in access to the lakebed to the eastern side of the lake, where the lake was adjacent to public land, points were not randomly placed with respect to the entire lake.

In addition, we surveyed any incidental shorebird habitat such as aquaculture ponds outside of the randomly selected blocks, flooded agricultural fields, sod farms, ponds, and riverbanks that we encountered en route to preselected survey sites. The cues for these incidental habitats were the presence of shallow water in the case of agricultural fields, the presence of mudflats or exposed shoreline in the case of ponds and riverbanks, and the presence of drawn-down ponds in the case of aquaculture. We also surveyed all sod farms encountered. For these incidental surveys, we sketched polygons of the habitat and labeled these polygons with the same four habitat descriptors as used in the other surveys. We also labeled these sketches with landmarks such as roads, large trees, and buildings. We then recorded the number and species of shorebird present, if any. At the end of the field season, the amount of habitat at these incidental surveys was estimated using sketches drawn in the field and aerial images ($\leq$2 m resolution) of the incidental survey sites.

Density Estimation

For agricultural and moist soil units, we estimated shorebird densities and total shorebird numbers using program Distance 5.0 (Thomas and others 2006b), which accounts for incomplete detection and differences in detection by habitat type. We truncated the largest 5–10 % of observations to limit error due to outliers (Buckland and others 2001) and line transect observations were left truncated by 5 m to account for the line (levee or road) not representing shorebird habitat. Detection functions were fit for each species separately, using only species with at least 40 detections, but detections for each species were pooled among survey sites of the same habitat type (agricultural or moist soil). Procedures for point counts at Catahoula Lake were similar with the exception that we grouped detections by shorebird size due to insufficient observations of individual species; detection functions were estimated from the pooled data but estimates of encounter rates and density were at the species level. Least (*Calidris minutilla*), Pectoral (*C. melanotos*), and Semipalmated Sandpipers (*C. pusilla*) were classified as small shorebirds, Stilt Sandpipers (*C. himantopus*) and Lesser Yellowlegs (*Tringa flavipes*) were classified as medium-sized shorebirds, and Greater Yellowlegs (*T. melanoleuca*) and Black-necked Stilts (*Himantopus himantopus*) were classified as large shorebirds. Point counts were only conducted at Catahoula during the second round due to the lack of appropriate habitat as heavy rains inundated the area during the first and third rounds.

Using the conventional distance-sampling engine, we fit three combinations of key functions and adjustment terms that are considered to be robust: the half normal and uniform key functions with a cosine adjustment and the hazard rate key function with simple polynomial adjustment (Buckland and others 2001). We also believed that differing degrees of visual obstructions at the survey locations might have affected detection so we incorporated vegetative cover and surface smoothness as covariates in model detection. For these models, we used the two key functions (hazard rate and half normal) and two series expansions (cosine and simple polynomial) that can be used with multiple covariate distance sampling. We ran models separately with both covariates, with only surface smoothness, and with only % vegetation cover and we used Akaike's information criteria (AIC) for model selection (Akaike 1973). For all analyses, estimates of the number of birds at survey locations were derived from the modeled averaged results. In the case of model uncertainty with covariate models, only the covariate in the top ranked model was included in the model averaging. The amount of shorebird habitat was determined using aerial photos and habitat polygons drawn in the field.

Using these detection-adjusted estimates of the number of shorebirds we then calculated the density of shorebirds by habitat category (drained aquaculture pond, moist soil unit, etc.). Because the number of shorebirds estimated or counted at each survey site followed a negative binomial distribution we modeled the number of shorebirds by habitat category using generalized linear models using the glm.nb function in the MASS package (Venables and Ripley 2002) in program R (R Core Team 2012) with a quadratic time effect and the log of area surveyed included as an offset.

Results

We observed 31,165 shorebirds of 28 species from 17 July to 23 September 2009 (Table 2). Six species: Least Sandpiper, Killdeer, Pectoral Sandpiper, Semipalmated Sandpiper, Black-necked Stilt, and Lesser Yellowlegs, accounted for 92 % of the observations.

Density Estimation

Only Killdeer were observed in agricultural areas during the surveys of randomly selected townships. Overall, 230 Killdeer in 99 groups were observed. More transects (10,940 m) were searched in the last round than in the first two rounds (1,900–2,610) as crops were harvested and more potential habitat became available within the surveyed townships. The detection model that had the lowest ΔAIC was the hazard rate with no series expansion using surface smoothness as a covariate (Table 3). The Cramér–von Mises goodness-of-fit statistic, which uses the overall departure between data and the fitted model, showed no significant problems using the best model ($W^2 = 0.044$, $0.9 < P \leq 1.0$). Model-averaged Killdeer density in harvested and fallow fields overall was 0.29 birds/ha (95 % confidence interval [CI] 0.15–0.55).

For moist soil units, Least Sandpiper (1,340 birds in 226 groups), Black-necked Stilt (1,039 birds in 317 groups), Lesser Yellowlegs (437 birds in 162 groups), Pectoral Sandpiper (650 birds in 118 groups), and Semipalmated Sandpiper (470 birds in 66 groups) all had a sufficient number of observations to estimate a detection function. Models for detection were similar among species; the hazard rate and half normal models with no terms in the series expansion had the most support. For species typically found in water (Black-necked Stilt and Lesser Yellowlegs) the covariate vegetative cover had the most support; for species more often found on mudflats (Least, Semipalmated, and Pectoral Sandpiper) the covariate surface smoothness had the most support although vegetative cover also received some support. As would be expected, detection distance decreased with higher vegetative cover and more lumps and mounds. The Cramér–von Mises goodness-of-fit statistic showed no significant problems using the best model for each species (all $P \geq 0.2$).

Table 2 Number of individuals by species observed during autumn migration 2009 in the lower Mississippi River Alluvial Valley

Species	Numbers
Black-bellied Plover (*Pluvialis squatarola*)	1
American Golden-plover (*Pluvialis dominica*)	1
Pacific Golden-plover (*Pluvialis fulva*)	1
Semipalmated Plover (*Charadrius semipalmated*)	195
Piping Plover (*Charadrius melodus*)	1
Killdeer (*Charadrius vociferus*)	4,964
Black-necked Stilt (*Himantopus himantopus*)	2,650
American Avocet (*Recurvirostra americana*)	26
Spotted Sandpiper (*Actitis macularia*)	146
Solitary Sandpiper (*Tringa solitaria*)	48
Greater Yellowlegs (*Tringa melanoleuca*)	355
Willet (*Catoptrophorus semipalmatus*)	4
Lesser Yellowlegs (*Tringa flavipes*)	2,034
Upland Sandpiper (*Bartramia longicauda*)	1
Ruddy Turnstone (*Arenaria interpres*)	1
Sanderling (*Calidris alba*)	12
Semipalmated Sandpiper (*Calidris pusilla*)	2,863
Western Sandpiper (*Calidris mauri*)	472
Least Sandpiper (*Calidris minutilla*)	13,753
Baird's Sandpiper (*Calidris bairdii*)	20
Pectoral Sandpiper (*Calidris melanotos*)	2,409
Dunlin (*Calidris alpina*)	2
Stilt Sandpiper (*Calidris himantopus*)	687
Buff-breasted Sandpiper (*Tryngites subruficollis*)	2
Short-billed Dowitcher (*Lymnodromus griseus*)	67
Long-billed Dowitcher (*Lymnodromus scalopaceus*)	407
Wilson's Snipe (*Gallinago delicata*)	3
Wilson's Phalarope (*Phalaropus tricolor*)	40

At Catahoula Lake we detected seven species over the three point counts during the second round of surveys; the hazard rate model, with or without the simple polynomial series expansion, was the best model for detection for all three size categories of shorebirds. Unlike the agricultural and moist soil datasets, there was no support for covariates at Catahoula, most likely due to the lack of variation in surface smoothness and vegetation cover at the points. The Cramér–von Mises goodness-of-fit statistic showed no significant problems using the best model for each of the three size types (all $P \geq 0.3$). Effective strip width (ESW) corresponded with shorebird size, with the largest species (Black-necked Stilt, Greater Yellowlegs) detected from the greatest distances (ESW = 322 m) whereas medium and small shorebirds were only detected

Table 3 Models of shorebird detection in the lower Mississippi River Alluvial Valley during autumn 2009

Data sets	Species	Model + series expansion	Covar.	*K*	ΔAIC
Agriculture	Killdeer	Hazard rate	sm	3	0.00
		Hazard rate	cov + sm	4	1.82
		Half normal	sm	2	4.86
		Half normal	cov + sm	3	6.47
Moist soil	Black-necked Stilt	Hazard rate	cov	3	0.00
		Uniform + cosine	cov + sm	4	1.13
	Lesser Yellowlegs	Half normal	cov	2	0.00
	Least Sandpiper	Half normal	sm	2	0.00
		Hazard rate	sm	3	0.70
		Half normal	cov + sm	3	1.95
		Hazard rate	cov + sm	4	2.61
	Semipalmated Sandpiper	Hazard rate	sm	3	0.00
		Half normal	sm	2	1.28
		Hazard rate	cov + sm	4	2.06
		Half normal	cov + sm	3	2.18
	Pectoral Sandpiper	Hazard rate	cov + sm	4	0.00
		Half normal	sm	2	1.65
		Half normal	cov + sm	3	2.64
		Hazard rate	sm	3	4.88
Catahoula	Small shorebirds	Hazard rate		2	0.00
		Uniform + cosine		1	1.73
		Half normal		1	2.45
		Uniform + simple polynomial		2	2.52
	Medium shorebirds	Hazard rate + simple polynomial		4	0.00
		Hazard rate		2	1.31
		Half normal + cosine		2	1.44
		Uniform + cosine		4	1.63
		Half normal		1	1.74
	Large shorebirds	Hazard rate		2	0.00
		Half normal cosine		2	5.70
		Half normal hermite		2	6.02

See Table 2 for scientific names of species

Models are ordered by Akaike's information criterion (AIC), *K* number of parameters, *ΔAIC* difference in AIC from the top model, *Covar.* covariates, *sm* level of surface smoothness, and *cov* % vegetative cover

considerably closer to the points (ESW = 176 and 109 m, respectively). Overall, estimated shorebird density at Catahoula (22.2 ± 14.3 birds/ha) was comparable to the mean shorebird density at federally managed moist soil units (22.9 ± 4.1 birds/ha).

Using the detection-adjusted results of the number of birds at each survey site increased the number of birds on public lands from 4 to 282 % over the raw counts, with the largest increases occurring at expansive sites with high levels of vegetative cover and surface roughness. For all public lands on a per survey basis, this represents a detection probability of between 0.35 and 0.96 and an increase in density from 10.7 (95 % CI 7.7–13.7) birds/ha to 15.7 birds/ha (95 % CI 11.2–20.3) birds/ha.

Sewage settling lagoons at Ensley Bottoms (86.7 birds/ha, 95 % CI 24.5–148.9) and aquaculture ponds (42.6 birds/ha, 95 % CI 26.7–58.4) had the highest estimated shorebird densities out of the habitats we surveyed (Fig. 3). Moist soil units on public lands (15.7 birds/ha, 95 % CI 10.6–20.3) had intermediate densities while agriculture (2.6 birds/ha, 95 % CI 0.4–4.9), borrow pits (2.4 birds/ha, 95 % CI 1.5–3.3), and sandbars (0.6 birds/ha, 95 % CI 0–1.7) all had low densities of shorebirds.

Discussion

Demonstrating a potential benefit of aquaculture to wildlife, drained aquaculture ponds had both high densities (33.5 birds/ha, 95 % CI 22.4–44.6) of shorebirds and a large amount of estimated available habitat (1,100 ha). In contrast to marine habitats, where aquaculture generally replaces natural shorebird habitat such as salt flats and tidal wetlands (e.g., Schaefer-Novelli and others 2006), in our

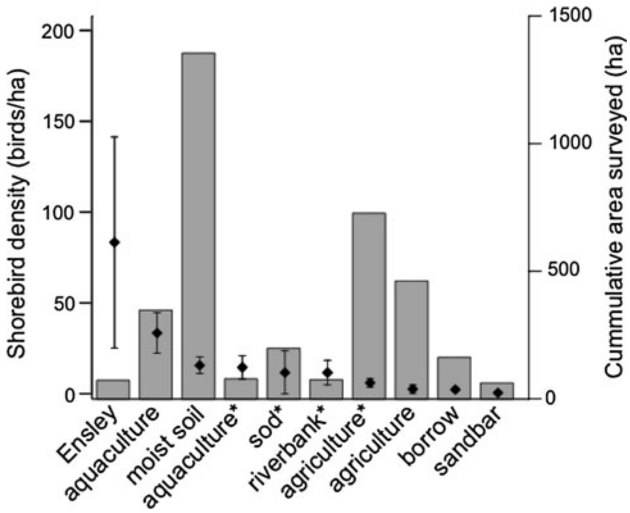

Fig. 3 Estimated shorebird densities (birds/ha) by habitat type for shorebirds during autumn migration of 2009 in the lower Mississippi River Alluvial Valley. *Error bars* indicate 95 % confidence intervals. *Barplot* on *second axis* indicates cumulative area (ha) of each habitat type surveyed. *Habitat encountered incidentally

region, aquaculture facilities were typically converted from row crops and thus created potential shorebird habitat from land that was not generally used by shorebirds during autumn migration. Although there are few studies of freshwater aquaculture and shorebirds, those that have been conducted tend to show positive relationships. Rettig (1994) reported high use of aquaculture ponds, with a high of 133 birds/ha at a crayfish complex in southwestern Louisiana. Huner (2006) found shorebirds as well as a wide variety of other bird species used crayfish aquaculture.

There are several possible explanations for the high shorebird densities we observed at drained aquaculture ponds in our study. Shorebird densities in areas that have been inundated for a period of several weeks or longer and then drawn down tend to be higher than areas that are flooded just before migration (Twedt and others 1998), probably due to higher invertebrate densities. Aquaculture ponds are often inundated for years before being drawn down. We could not find any published estimates of invertebrate densities in drained aquaculture ponds but Huner (2006) stated that crayfish ponds supported high densities of invertebrate prey, especially insect larvae, crustaceans, and annelid worms.

Food density in settling lagoons is likely also high, possibly due to the high nutrient content in the settling lagoons. In a comparison of macroinvertebrates between sewage settling lagoons at Ensley Bottoms and mudflats at moist soil units in Tennessee, Ensley Bottoms had a significantly higher macroinvertebrate biomass (5.00 ± 3.33 g/m^2) than the mudflats (2.17 ± 1.27 g/m^2; Augustin and others 1999). This high density of shorebird food availability may explain the high shorebird densities (83.4 birds/ha, 95 % CI 25.3–141.5) observed at Ensley Bottoms.

Distance-based methods have rarely been used with shorebirds due to issues of heterogeneous and patchy habitat and perceived violations of assumptions (but see Jorgensen and others 2008). Incomplete detection of shorebirds is almost certain in vegetated habitat as demonstrated by Farmer and Durbian (2006) who estimated detection probability using flush counts to adjust raw observations. Shorebird habitat in Farmer and Durbian (2006) was divided into three categories: light, medium, and heavily vegetated; the moist soil surveys in this study were most comparable with the light and medium vegetation categories. Farmer and Durbian (2006) calculated detection probabilities ranging from 0.34 to 0.97 in the light and medium vegetation categories, nearly identical to the range of detection probabilities in this study (0.35–0.96). With attention paid to the assumptions required for distance-based sampling, and care regarding habitat delineation and recording of covariates likely to affect detection, distance-based methods can be used for correcting shorebird counts under some circumstances. Using only the raw counts, we would have underestimated the importance of moist soil habitat to shorebirds; using the raw counts we estimated 10.7 (95 % CI 7.7–13.7) birds/ha whereas after adjusting for incomplete detection we estimated 15.7 (95 % CI 11.2–20.3) birds/ha.

Shorebird use of habitat in the interior is highly dynamic and unpredictable from year to year and our habitats followed this trend. Shorebird habitat at moist soil units frequently became inundated, overgrown with tall, dense vegetation, or dried out between survey rounds during 2009, illustrating the difficulty in predicting the importance of any one site. Shorebird use of aquaculture habitat was similarly difficult to predict on a fine spatial scale in that the creation of shorebird habitat depended on the impoundment maintenance schedules at these facilities. Catahoula Lake can support large numbers of shorebirds, however, during periods of high precipitation shorebird use can be very low because shallow water and mudflat habitat are inundated (Hayden, Wildlife Biologist, Louisiana Department of Wildlife, and Fisheries personal communication). During high water levels Catahoula Lake covers over 100 km^2 and, historically, Catahoula has a normal seasonal water level variation of 7.6 m and an extreme variation of 12.2 m (Brown 1943). Because of the high variability in water levels at Catahoula, the amount of shorebird habitat at Catahoula is highly variable both within and among years. This high variability underscores the importance of the availability of other shorebird habitat.

We know from observations of shorebirds using flooded rice, soybean, and fallow fields that shorebirds do use agricultural habitat in the LMAV. However, we did not observe any shorebirds other than Killdeer using agricultural habitats in our standardized random surveys; low densities of other shorebird species were observed in our incidental agricultural surveys. Agricultural areas have been demonstrated to be important to shorebirds during the non-breeding season and during spring migration (Taft and Haig 2005; Niemuth and others 2006; Ogden and others 2008); in the LMAV, flooded soybean and rice fields were heavily used by Killdeer and Wilson's Snipe from November to March (Twedt and others 1998). In addition, preferential use of agricultural land at night was observed by Dunlins (*Caladris alpina*) in British Columbia (Shepherd and others 2003); indicating diurnal surveys may underestimate the importance of agricultural habitat to shorebirds. Because most crops are not harvested until mid- to late September in the LMAV, the amount of agricultural habitat suitable for shorebirds was limited during the period we surveyed. Shorebird usage of agricultural habitat during the winter and late autumn migration is likely to be higher than indicated from this study.

Conclusions

Although aquaculture has contracted in recent years in response to economic pressures, based on pond maintenance schedules, there were still nearly 900 ha of shorebird habitat available in 2012, nearly half of the estimated requirement of 2,000 ha by the LMAV Joint Venture working group (Loesch and others 2000). The future of aquaculture in the LMAV is unknown but at the current rate of loss, autumn-migrating shorebirds will have to rely more on other habitats for resting and foraging. Recognition of the current aquaculture habitat trends will be important to the future management activities of federal and state agencies. Should these aquaculture habitat trends continue, there may be a need for the LMAV Joint Venture to investigate other habitats that can be managed to offset the current and expected loss of aquaculture acreages. This study illustrates the potential for freshwater aquaculture to create habitat for a taxa at risk. Aquaculture is a rapidly growing industry worldwide; wildlife may be better managed by the identification of benefits as well as risks of aquaculture development and practices.

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