

Synchronizing conservation to seasonal wetland hydrology and waterbird migration in semi-arid landscapes

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Citation: Donnelly, J. P., D. E. Naugle, D. P. Collins, B. D. Dugger, B. W. Allred, J. D. Tack, and V. J. Dreitz. 2019. Synchronizing conservation to seasonal wetland hydrology and waterbird migration in semi-arid landscapes. *Ecosphere* 10(6):e02758. 10.1002/ecs2.2758

Abstract. In semi-arid ecosystems, timing and availability of water is a key uncertainty associated with conservation planning for wetland-dependent wildlife. Wetlands compose only 1–3% of these landscapes; however, large populations of migratory waterbirds rely on these wetlands to support energetically demanding life history events such as breeding and migration. Migration is considered a crucial period for birds associated with individual survival and reproductive success, yet our understanding of migration ecology remains limited. To better inform conservation planning supportive of these demands, we quantified synchrony of wetland flooding and waterbird migration by reconstructing bi-monthly surface water patterns from 1984 to 2015 across 11.4 million ha of the semi-arid Great Basin, USA. Results were then linked to seasonal migration chronologies for seven dabbling ducks species. Seasonal patterns were used in landscape planning simulations to assess efficiency in conservation strategies that aligned temporally sensitive wetland flooding and species migration. Wetland data were combined with land tenure to evaluate periodicity in waterfowl reliance on public and private lands. We found migration chronologies misaligned with wetland flooding. In spring, half (43–59%) to three-quarters (68–74%) of seasonal wetlands were flooded and available to early- and late-migrating species while seasonal drying restricted wetland flooding to 13–20% of sites during fall migration. Simulations showed wetland conservation inconsiderate of temporal availability was only 67–75% efficient in meeting waterfowl habitat goals on private lands that made up ~70% of flooded wetland area in spring. Private–public wetland flooding was equivalent during fall migration. Accounting for spatiotemporal patterns of wetland flooding is imperative to improving efficiencies linked to migratory bird conservation. Timing of public–private wetland flooding, demonstrated by our models, provides landscape context that emphasized a joint role in supporting migratory waterbird habitat. Integrated management scenarios may capitalize on public lands’ flexibility to expand fall flooding to offset seasonal drying on private lands while targeted incentive-based conservation assures private wetland flooding in spring. Such scenarios illustrate benefits of holistic public–private wetlands management representing a forward-looking alternative that aligns conservation with forecasts of increasing water scarcity.

Key words: conservation; flood irrigation; migration chronology; ranching; seasonal wetland; semi-arid; water; waterfowl.

Received 20 November 2018; revised 14 April 2019; accepted 22 April 2019. Corresponding Editor: Paige S. Warren.

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INTRODUCTION

In arid and semi-arid ecosystems, a key uncertainty associated with planning for the conservation of wetland-dependent wildlife is the quantity and timing of water (i.e., habitat) availability. These systems are defined by relatively low precipitation and excessive evapotranspiration that drive seasonal patterns of surface water availability (Williams 1999). Arid and semi-arid regions account for 40% of terrestrial land surface globally and support upward of 2 billion people (Gilbert 2011). Annual and intra-annual variability in precipitation is typical with distinct dry seasons and unpredictable prolonged droughts that lead to temporally and spatially dynamic wetland flooding patterns (Jolly et al. 2008).

Wetlands compose only 1–3% of landscapes in semi-arid ecosystems (Tiner 2003); however, large populations of migratory waterbirds rely on these habitats to support energetically demanding life history events such as migration and breeding (Bellrose 1980, Skagen et al. 1999). Migration is a crucial period for many birds due to its important link to individual survival and breeding success (Drent et al. 2003). However, our understanding of migration ecology remains limited in comparison with breeding and wintering periods that have been the focus of research and conservation efforts (Arzel et al. 2006, Skagen et al. 2008). Migratory behavior poses challenges to habitat monitoring that must account for dynamic resource conditions and bird movements over large temporal and spatial scales (Haig et al. 1998, Skagen et al. 2005). Efficient waterbird habitat conservation must account for these complexities to assure timing of seasonal wetland flooding and species migration chronology align (Albanese et al. 2012, Beatty et al. 2014).

Waterfowl have long served as model organisms in landscape and community ecology (Krapu et al. 1983, Nichols et al. 1995, Austin

et al. 2001, Notaro et al. 2016, e.g., Schummer et al. 2017, Kleyheeg et al. 2017). Waterfowl undergo large, highly visible migrations and experience cross-seasonal influences with habitat conditions on wintering and migration areas influencing subsequent reproduction (Ankney and MacInnes 1978, Sedinger and Alisauskas 2014, Osnas et al. 2016). In North America, waterfowl have been the source of intense research focus for many decades; thus, details of movement pathways are comparatively well known (Baldassarre 2014). Landscape conditions supporting migration, however, remain poorly understood (Stafford et al. 2014), particularly in arid regions where water resources are least predictable and difficult to quantify. It was our objective, therefore, to understand resource dynamics supporting waterfowl migration by examining temporal alignment of bird movement and seasonal wetland flooding.

To quantify synchrony of wetland flooding and waterfowl migration, we reconstructed bi-monthly seasonal surface water hydrology from 1984 to 2015 in portions of the semi-arid Great Basin, USA, to estimate spatiotemporal patterns of wetland flooding. Wetland flooding was then linked to timing of seasonal migration for seven species of dabbling ducks: American wigeon (*Mareca americana*), gadwall (*M. strepera*), cinnamon teal (*Spatula cyanoptera*), northern shoveler (*S. clypeata*), green-winged teal (*Anas carolinensis*), mallard (*A. platyrhynchos*), and northern pintail (*A. acuta*), hereafter waterfowl. Seasonal patterns were used in landscape planning simulations to assess conservation efficiency that aligned temporally sensitive wetland flooding and species migration. Wetland data were also combined with land tenure to evaluate periodicity in waterfowl reliance on public and private lands. Study outcomes provide new temporal context of wetland and waterfowl interactions to guide landscape strategies that assure conservation measures translate to population benefits.

METHODS

Study area

The study area encompassed palustrine wetlands and riparian floodplains across 11.4 million ha of the northern Great Basin, USA (Fig. 1a). The study area boundary was defined by merging United States Geological Survey watershed polygons coincident with wetland footprints (<http://nhd.usgs.gov>). Regional wetlands act as an important migratory hub for waterbirds, connecting western North American wintering and breeding grounds (e.g., Miller et al. 2005). Climate patterns are characterized by cold wet winters and hot dry summers. Wetland flooding is induced by spring runoff tied to high-elevation snowmelt. Most wetlands are flooded seasonally, late winter through early summer, after which evaporative drying reduces surface water availability. Wetland resources (Fig. 1b) are concentrated in productive valley bottoms across ownership boundaries including large, publicly managed wildlife refuges. Private wetlands were made up primarily of flood-irrigated hay meadows managed for livestock forage and cattle ranching. Patterns of wetland flooding can be

influenced by variability in annual precipitation rates which one in five years fall to 75% of normal (Miller et al. 1991, Donnelly et al. 2018).

Modeling wetland surface water dynamics

Abundance and timing of wetland flooding was modeled from 1984 to 2015 using Landsat 5 Thematic Mapper (1984–2012) and Landsat 8 Operational Land Imager (2013–2015) satellite imagery. Surface water extent was measured using constrained spectral mixture analysis (SMA; Adams and Gillespie 2006) that allowed proportional estimations of water contained within a continuous 30 × 30 m pixel grid (Jin et al. 2017). This approach provided an accurate account of flood extent when only a portion of surface water was visible within grid cells, due to sample grid misalignment or interspersion of water and emergent vegetation (DeVries et al. 2017), a common characteristic among shallow seasonal wetlands in semi-arid regions (Jolly et al. 2008; see Appendix S1 for methods outlining SMA training data collection).

Wetland flooding models were binned into six continuous multi-year periods correlated to oscillations in above- and below-average precipitation

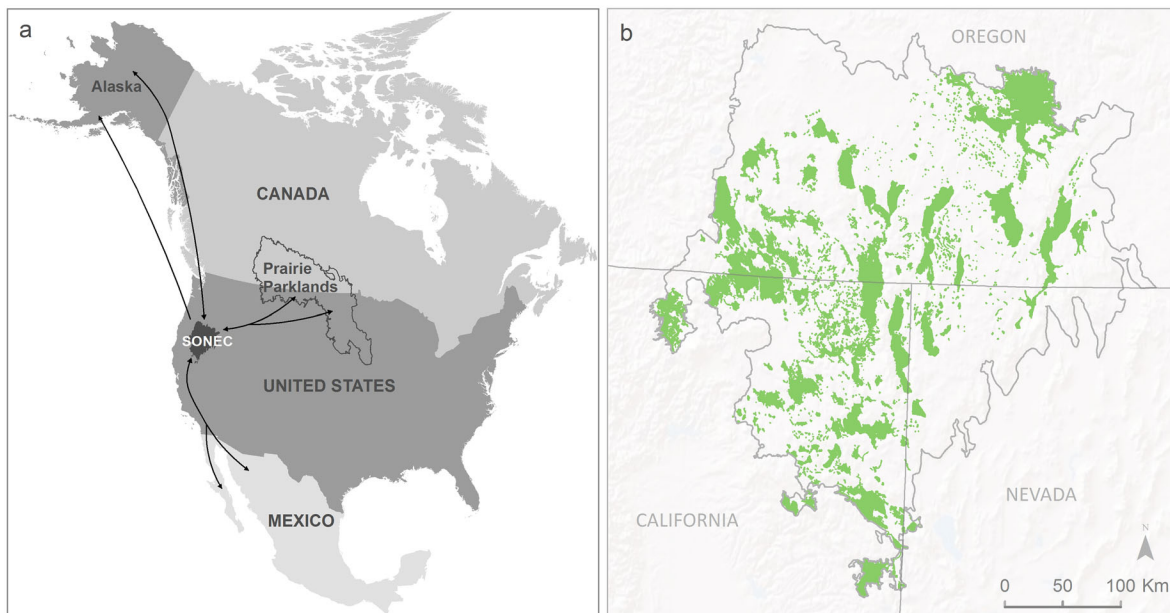


Fig. 1. Study area in context of western North America waterbird migration routes depicted as arrowed lines linking common breeding (Alaska and Prairie Potholes) and wintering regions (a). Wetland footprint monitored within study area shown in green (b).

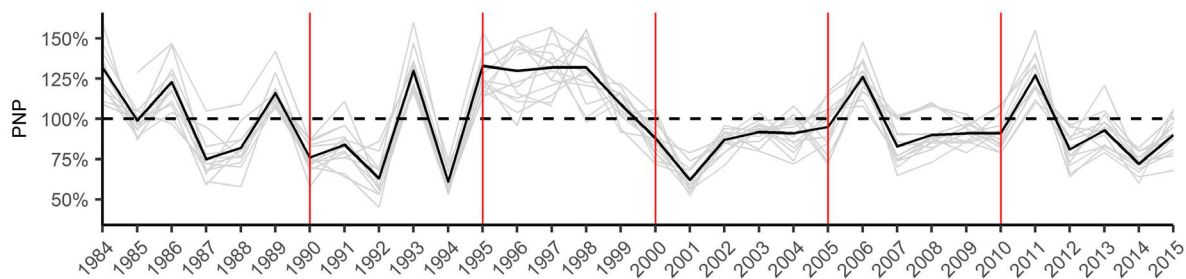


Fig. 2. Annual percent normal precipitation (PNP) mean for study period (1984–2015; black solid line). Gray lines depict within study area variance. Wetland monitoring was binned and averaged within distinct multi-year precipitation trends marked by red lines.

trends estimated for the study period using data from 14 SNOTEL weather stations (<https://www.wcc.nrcs.usda.gov/snow/>; Fig. 2). Trends were calculated within water years from 1 October to 30 September. Landsat satellite imagery collected within multi-year bins were partitioned further into two-week periods by their day of year acquisition to align wetland conditions with bi-monthly waterfowl surveys used in our analysis. The first period began mid-January and ran continuously to mid-December. Satellite data within two-week bins were averaged into single multi-spectral images and classified using SMA to produce bi-monthly estimates of wetland flooding for each multi-year period. Applying this approach made it possible to isolate climate-driven ecological means influencing wetland response (e.g., drought) and simultaneously reduced the potential of monitoring gaps in Landsat data caused by clouds and cloud shadow. A gap in satellite coverage prevented monitoring in 2012.

Bi-monthly estimations of wetland flooding were clipped and summarized spatially within digitized wetland, riparian, and agricultural boundaries, hereafter wetland polygons. This process minimized the potential of false water positives by removing anthropogenic features (e.g., buildings and asphalt) and topographic shadow known to be misclassified as water when using SMA (DeVries et al. 2017). Due to high interspersed rates of emergent vegetation and water, we found proportional surface water estimates seldom reflected true flooded grid cell area and assumed the entire cell inundated when water was present. Because of reduced detectability grid cells containing surface water

proportions, <10% were omitted from summaries to minimize over estimation of wetland flooding.

Annual wetland hydroperiods were classified by summarizing bi-monthly presence of water within grid cells. Cells containing surface water six months or less were classified as seasonally flooded while those over six months were classified as semi-permanently or permanently flooded (Cowardin et al. 1979). This approach accounted for seasonal wetlands that occur along the shallow fringe of endorheic lakes, reservoirs, and semi-permanent wetlands as a result of changing water elevations. Because wetland hydrology is considered an indicator of waterbird habitat use (Baker 1979, Isola et al. 2000, Ma et al. 2010), we masked semi-permanent and permanently flooded areas from our models to align wetland resources with the suite of dabbling duck species used in our analysis that rely primarily on seasonally flooded habitats during migration (Smith et al. 1989). Flooded wetland area was assumed to represent trends in habitat availability; however, we acknowledge variance in habitat condition and quality can also influence overall resource value for waterbirds (González-Gajardo et al. 2009).

Migration chronology

We constructed spring and fall waterfowl migration chronology using bi-monthly aerial surveys collected over portions of the study area from 1984 to 2015. Flights began in early September and continued through April. Surveys were flown along standardized routes in a single-engine high-wing aircraft at a speed of 140–150 km/h 30–50 m above terrain. Birds were

seldom flushed to reduce potential of double counting (Gilmer et al. 2004); two individuals completed nearly all surveys potentially reducing survey bias (Frederick et al. 2003). Surveys covering 20% of area were assumed to represent the broader region. Proportional abundance of waterfowl species was uniform in repeated surveys covering ~90% of area in 2002 and 2003 (Fleskes and Yee 2007). Thirty-two years of bi-weekly ground counts within the region (1984–2015) reaffirmed that trends in abundance were proportional over time. We aggregated aerial surveys for this comparison because ground counts did not distinguish between species.

Waterfowl survey data were divided into spring (1 February–30 April) and fall (1 September–15 December) migration and binned temporally into six multi-year periods of above- and below-average precipitation trends used in wetland modeling (Fig. 2). Within bins, counts were combined to estimate migration chronologies. This approach made it possible to isolate climate-driven ecological means influencing waterfowl migration that aligned bird response to wetland variance normalized across years (Gilmer et al. 2004). Results were summarized as box plots showing lower (25%), middle (50%), and upper (75%) quartiles as dates representing a proportional abundance of species migration through the region. Middle quartile dates were considered mid-migration points closely aligned with peak bird abundance. Species box plots were overlaid on graphs that contained our area estimates of wetland flooding to compare temporal alignment of migration and wetland pulse dynamics.

Land ownership and wetland dynamics

Bi-monthly abundance (ha) of wetland flooding was partitioned by ownership and plotted as study period means to estimate annual trends. Ownership was assigned with Bureau of Land Management surface land ownership data (sagemap.wr.usgs.gov) using a GIS. Spring and fall migration chronologies were linked to ownership as an estimate of potential public–private wetlands' reliance. Proportional ownership of flooded wetlands was calculated for each species by averaging public–private areas flooded between first- and third-quartile migration date means. Overall proportion of wetlands flooded

was also calculated for each species as a ratio of flooded wetland area between first- and third-quartile migration date means vs. peak flooding averaged for the study period.

We estimated temporal predictability of seasonal wetland flooding by summarizing bi-monthly presence–absence of surface water throughout the study period. Comparisons were made between multi-year wetland means ($n = 6$; Fig. 2). Presence–absence of surface water was determined at the wetland polygon level. Surface water was summarized within polygons using a zonal statistical function. Temporal predictability was calculated as a probability of flooding within the same two-week period. Polygon ($n = 28,703$) probabilities were averaged within bi-monthly periods and summarized across spring and fall waterfowl migration chronologies. Polygons with zero probability of flooding were excluded from calculations.

Measuring conservation efficiency

Wetland surface water models were used (1984–2015) to simulate the efficiency of random vs. targeted approaches to wetlands' conservation that increasingly aligned temporal habitat availability (i.e., wetland flooding) and chronology of spring waterfowl migration. Efficiency was defined as the rate conservation measures resulted in resource availability temporally aligned with wildlife need. We ran simulations for wetlands on private lands because agriculturalists had the greatest influence on habitat availability through changes in timing and duration of flood irrigation (see *Results*; Fig. 4). A habitat objective of 8000 flooded wetland hectares, supportive of early-migrating waterfowl populations (14–28 February), was estimated as a proxy for simulations. Habitat need was calculated by scaling regional habitat objectives (NRCS 2013) proportionally to fit temporal waterfowl abundance using averaged counts from bi-weekly aerial surveys (1984–2015). Simulations randomly conserved wetland polygons and summed separately their flooded area means for all-spring migration (1 February–30 April) and early-spring migration (14–28 February). Each simulation ($n = 1000$) continued until all-spring migration flooding totaled 8000 ha. Simulations were repeated in stepwise fashion so as to improve model efficiency by restricting selection of

wetlands to those with increasing probability ($f = \sim 15\%$) of early-spring flooding. We replicated analyses to compare efficiencies for late-migrating species (01–15 April). Simulations were fit to a generalized additive model and plotted to examine temporal alignment of migration and habitat availability within wetland areas conserved.

Data processing

All image processing and raster-based analyses were conducted using Google Earth Engine cloud-based geospatial processing platform (Gorelick et al. 2017). Vector-based processing was completed using QGIS (qgis.osgeo.org). Plotting and statistical analyses were completed using the R Base Package (R Core Team 2015).

RESULTS

Peaks in seasonal wetland flooding were stable ($SD \pm 9\%$) during this 32-year study. Prolonged drought in the early 1990s that reduced flooded area to 224,523 ha was followed by elevated inundation (276,571 ha) in the latter part of the same decade (Figs. 2 and 3b, c). Wetland flooding also fluctuated annually (Fig. 3), peaking in early April ($SD \pm 4$ weeks) and drying again by early November ($SD \pm 4$ weeks). Wetland flooding was 3.5-fold higher in spring than in fall. Timing of agricultural flood irrigation elevated flooded wetland acreage in April, May, and August (Fig. 3).

Abundance of early-spring migrants (American wigeon, mallard, northern pintail) typically peaked 2–6 weeks before their later-arriving counterparts (cinnamon teal, gadwall, green-winged teal, northern shoveler; Table 1, Fig. 3). On their way back south, early fall migrants (cinnamon teal and gadwall) peaked in their abundance 3–5 weeks ahead of later-arriving species (American wigeon, green-winged teal, mallard, northern pintail, and northern shoveler; Table 1, Fig. 3). Migration peaks for individual species across periods were similar in spring ($SD \pm 5$ – 8 d) and fall ($SD \pm 5$ – 11 d) with the exception of spring cinnamon teal ($SD \pm 19$ d). Half of the birds, by species, migrated through the region within 21–28 and 33–42 d in spring and fall, respectively. Fall migrating cinnamon teal were

an outlier with half of all birds passing through the region within nine days. Species migration chronologies were comparable to patterns previously described (Bellrose 1980).

Migration chronologies were partially misaligned with wetland flooding in spring and fall (Fig. 3). In spring, only half (43–59%) to three-quarters (68–74%) of seasonal wetlands were flooded and available to early- and late-migrating species, respectively (Table 2). Late- and early-arriving species had already moved through the region four and eight weeks before peaks in wetland flooding (Fig. 3). Fall migrants moved through when wetland flooding was at or near annual lows (13–20%; Table 2).

Patterns in relative wetland flooding varied with land ownership. From 1984 to 2015, 60–70% ($SD \pm 5$ – 7%) of wetlands flooded during spring migration were privately owned; in fall, public-private ownership was equivalent (Table 3, Fig. 4). Public wetlands on wildlife refuges that were actively managed for waterfowl comprised 18% of seasonally flooded sites during spring and fall migration; other publicly owned wetlands contributed an additional 15–19%, respectively. Despite lower abundance, average timing of wetland flooding was more predictable on publicly managed lands with 58% ($SD \pm 12\%$) of sites inundated during the same period each spring compared to 43% ($SD \pm 17\%$) on private lands. Flooding predictability remained higher on public ($\mu = 50\%$; $SD \pm 15\%$) vs. private lands ($\mu = 39\%$; $SD \pm 10\%$) in fall when wetland flooding was most limiting (Fig. 4). Wetland predictability was lower for early-arriving species in spring. All species experienced lower predictability of wetland flooding in fall vs. spring migration (Table 4).

On private lands, simulations show that a completely random approach to wetlands' conservation is only 67% efficient in providing the desired 8000 ha of flooded habitat for early-migrating waterfowl (Fig. 5). Efficiency increased marginally (75%) for later-migrating species whose movements were more temporally aligned with seasonal wetland flooding (Fig. 3). Given these known inefficiencies, uninformed conservation measures would have to exceed existing habitat goals of privately owned wetlands by 25–33% to support spring migration. Using spatial data from this study to strategically

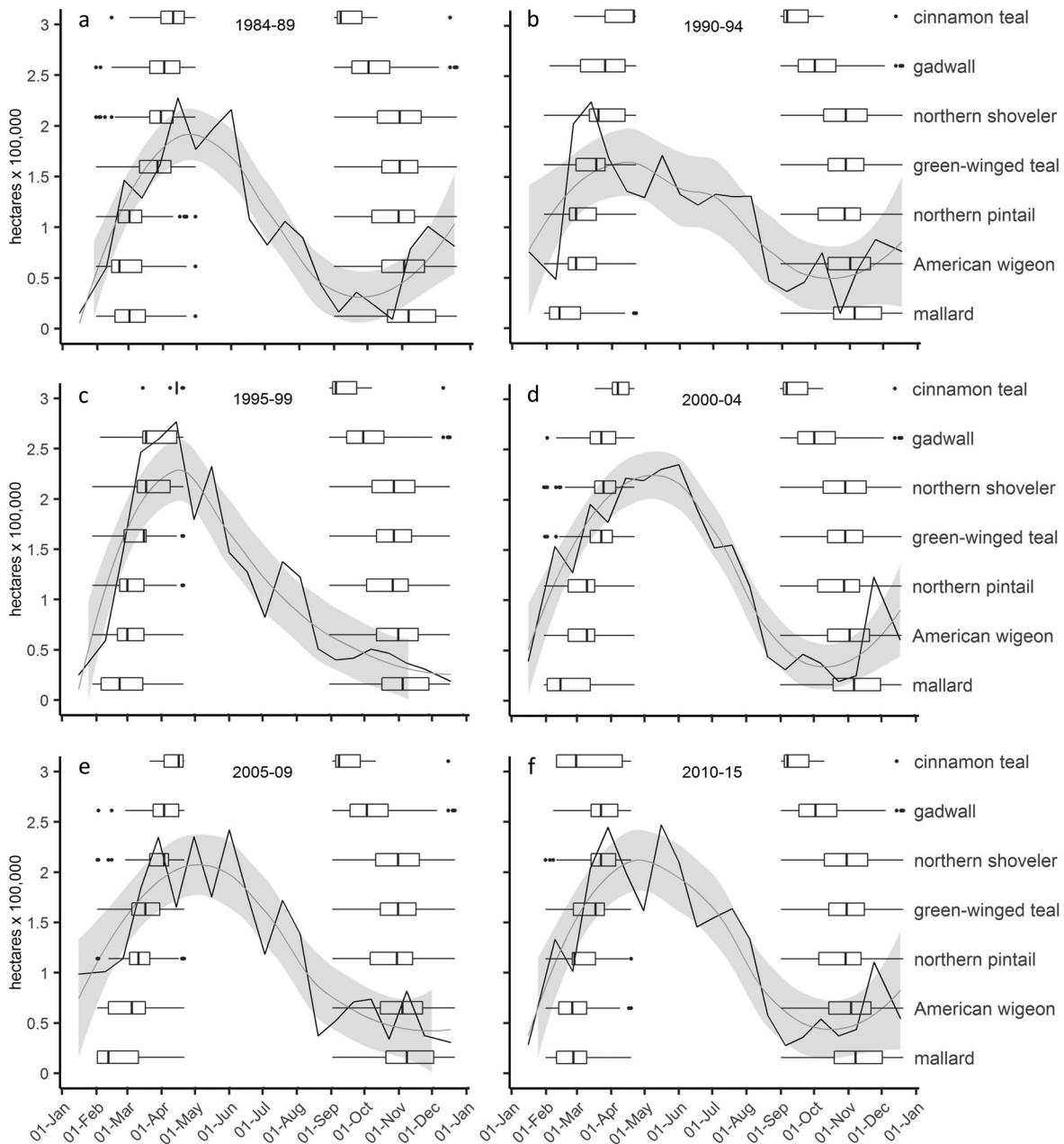


Fig. 3. Bi-monthly abundance of flooded seasonal wetlands (solid black lines) fit with polynomial regressions and overlaid with spring (February–May) and fall (September–December) waterfowl migration chronology. Bird migrations depicted as box plots shown as relative species abundance over time. Panels (a–f) correlate to multi-year precipitation trends used to bin wetland and migration response; see Fig. 2.

conserve wetlands that are reliably wet during migration would improve conservation in near-linear fashion once a 50% rate of efficiency is attained (Fig. 5).

Overall wetland model accuracy was 95% with averaged accuracies ranging from 93% to 98% within proportional water cover classes (10–32, >32–55, >55–78, and >78–100%). Accuracy was

Table 1. Average peak spring and fall species migration date (1984–2015).

Species	Spring	SD ± days	Fall	SD ± days
American wigeon	28-Feb	6	28-Oct	6
Cinnamon teal	6-Apr	19	9-Sep	6
Gadwall	25-Mar	7	30-Sep	5
Green-winged teal	19-Mar	5	28-Oct	5
Mallard	20-Feb	8	23-Oct	9
Northern pintail	5-Mar	5	23-Oct	5
Northern shoveler	25-Mar	7	18-Oct	11

Table 2. Percentage seasonal wetland areas flooded during peak species migration (1984–2015).

Species	Spring (%)	Fall (%)
American wigeon	54	17
Cinnamon teal	68	13
Gadwall	72	19
Green-winged teal	72	20
Mallard	43	17
Northern pintail	59	13
Northern shoveler	74	17

Table 3. Percentage ownership of flooded wetlands during peak species migration (1984–2015).

Species	Private spring (%)	Public spring (%)	Private fall (%)	Public fall (%)
American wigeon	70	30	53	47
Cinnamon teal	60	40	49	51
Gadwall	62	38	59	41
Green-winged teal	62	38	53	47
Mallard	70	30	53	47
Northern pintail	70	30	53	47
Northern shoveler	62	38	51	49

lower among sites containing proportionally lower surface water abundance. High accuracy was attributed to confinement of the model to potential wetland areas that reduced false water positives correlated to non-wetland features (e.g., buildings and asphalt) and topographic shadow (DeVries et al. 2017). Accuracy was comparable to similar time-series wetland inundation studies using Landsat data (Jin et al. 2017).

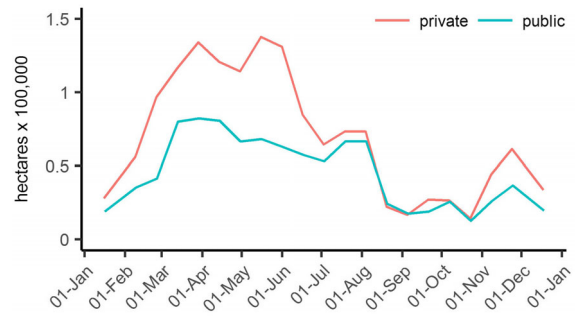


Fig. 4. Mean bi-monthly abundance of seasonal wetlands flooded on public and private lands (1984–2015).

Table 4. Temporal predictability of seasonal wetland flooding during peak species migration (1984–2015).

Species	Spring (%)	SD (%)	Fall (%)	SD (%)
American wigeon	48	±11	42	±13
Cinnamon teal	55	±14	49	±16
Gadwall	54	±14	49	±15
Green-winged teal	52	±13	44	±12
Mallard	45	±11	42	±12
Northern pintail	48	±12	44	±13
Northern shoveler	54	±13	44	±14

DISCUSSION

Our models are the first to quantify the long-term temporal patterns of seasonal wetland hydroperiod across a large geographic region and to link complexities of agricultural water use (e.g., western water rights) into a set of conservation scenarios to better align wetland conservation with avian migration chronologies. Findings reiterate that in semi-arid western North America wetland flooding is tightly linked to seasonal climatic variation (Rajagopalan and Lall 1998) regardless of land tenure and emphasize that private lands are important for meeting wetland conservation needs, particularly in spring. Unlike many landscapes where wetlands have been significantly reduced by drainage and development (Dahl et al. 1991), seasonally flooded wetland complexes remained spatially abundant yet temporally dynamic through the period of record with the exception of drought in the early 1990s (see Fig. 3). Instead of overcoming wetland loss, the conservation challenge appears to lie in the

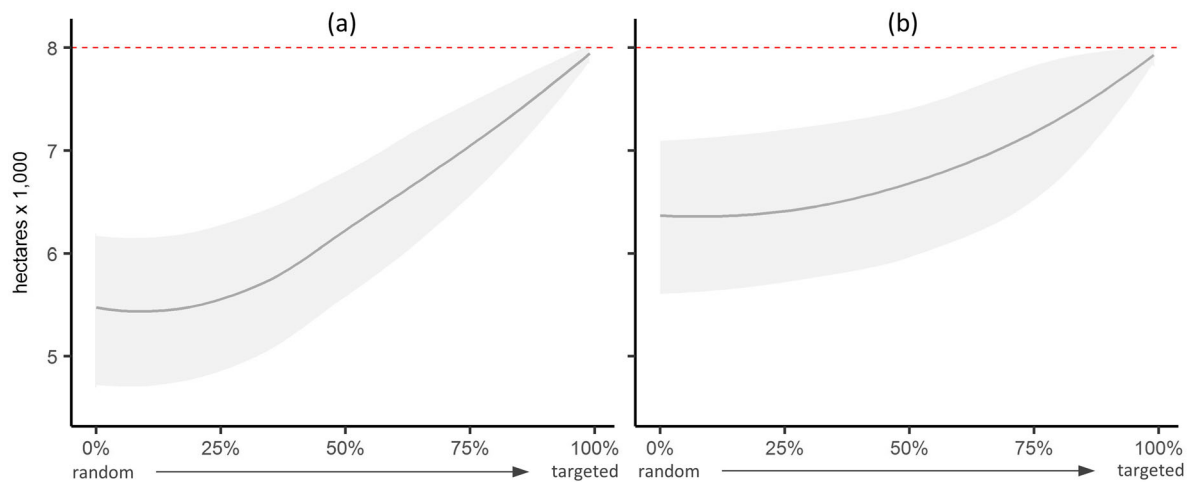


Fig. 5. Simulated outcomes of wetland conservation efficiency for late February (a) and early April (b). Dashed red line identifies approximated flooded wetland habitat objective (8000 ha) for spring migrating waterfowl. Solid black line predicts gap in wetland area conserved and flooded area available along increasing temporal alignment with species migration chronology derived from random to 100% targeted actions. Gray ribbon identifies standard deviation.

maintenance of existing wetland hydrology (Table 4) and its alignment with habitat needs of migratory waterbirds (Skagen et al. 2005, Beatty et al. 2014, Kleyheeg et al. 2017).

Misalignment of migration chronology with flooded wetland abundance in spring and fall (Table 2, Fig. 3) likely reflects life history trade-offs wherein migratory waterbirds must balance energetics with resource availability that enable them to successfully survive and reproduce (Skagen and Knopf 1993, Arzel and Elmberg 2004, Sedingner and Alisauskas 2014). The quantity and quality of spring migration habitat is known to influence waterbirds' breeding propensity and recruitment (Gunnarsson et al. 2005, Morrison et al. 2007, Devries et al. 2008, Zarzycki 2017). In the semi-arid west of North America, fall migrants have evolved to navigate drying wetland landscapes (e.g., Plissner et al. 2000), but food availability could become limiting if water scarcity increases (Dettinger et al. 2015). Observed fall bottlenecks in flooded wetland abundance for migrating waterfowl raise concerns over future vulnerability to climate change and predictions of more frequent and intensifying drought (Trenberth et al. 2003). Unmet energetic demands resulting from increased fall drying could manifest as cross-seasonal effects that limit populations (e.g., Schmutz and Ely 1999).

Until now, most wetland conservation strategies have been unable to account for ecological uncertainty to ensure distinct waterbird populations are supported with enough options to rest and refuel during migration (Arzel et al. 2006, Skagen et al. 2008). Patterns indicate privately owned flood-irrigated hay meadows, first settled in the late 1800s for their persistent water resources (Sauder 1989), remain a major driver of habitat abundance seasonally. Hay meadow sites were unique in that they were confined to riparian floodplains and lowlands. We speculate most functioned historically as seasonal wetlands, and those identified in our models continue in part to provide wetland value (Peck and Lovvorn 2001). Meadow hydrology today is influenced by water law in the west of the United States that structures timing of irrigation and flooding in early to late spring when water is first made available to growers and again in mid-summer when fields are re-flooded to promote regrowth after hay cutting. Waterbird reliance on agricultural wetlands is well documented, and while natural systems exhibit greater ecosystem benefit, seasonal waterbird utilization provides important habitat niche compatible with existing water-use practices.

The landscape context provided by scenario planning suggests a previously unknown flexibility that resource managers might exploit to offset

patterns of fall water scarcity and better align wetland flooding with waterfowl migration. Spring flood irrigation on private hay meadows that already support ~70% of seasonally flooded wetlands holds additional promise for further bolstering habitat availability. Emerging management opportunities may include voluntary incentives providing conservation protections to spring wetland flooding on private lands that better align existing flood irrigation with waterbird migrations when outcomes provide mutual benefits to agriculture and wildlife. Publicly managed wildlife refuges in turn could opt to shift spring water allocations to fall migration to meet limited habitat needs by offsetting deficits created by seasonal drying on private lands (see Fig. 4). Capitalizing on flexibility of public lands flooding to bolster wetland flooding during fall migration would represent a major departure from management scenarios supportive of important spring migration habitat (Devries et al. 2008, Zarzycki 2017), but may prove a feasible option considering climate change forecasts of increasing water scarcity (Trenberth et al. 2003).

Sustaining migration hinges on our ability to maintain dynamism in both ecological processes and the associated water-use practices that foster and maintain wetland hydrology (Albanese et al. 2012). Our findings emphasize the joint role of public–private wetland resources in supporting migratory waterbirds and highlight the importance of managing multiple ownerships as an integrated system (e.g., Beatty et al. 2014). While the focus of this work is placed on waterfowl, outcomes are applicable to conservation of all migratory waterbird species. In arid landscapes, predictions of increased climate variability are likely to intensify resource bottlenecks (e.g., fall migration) triggering temporal mismatches in wetland flooding and energetically demanding migration events (e.g., Maron et al. 2015). To bolster landscape resiliency, we encourage development of conservation strategies considerate of ecological synchrony that maintain wetland function aligned with migratory waterbird needs.

ACKNOWLEDGMENTS

We thank the National Resources Conservation Service in Oregon for their funding, leadership, and vision that made development of this project possible.

We too thank the Intermountain West Joint Venture for funding this work. We are grateful to those who collected and provided waterfowl survey data: U.S. Fish and Wildlife Service—Klamath Basin National Wildlife Refuge Complex and Oregon Department of Wildlife—Summer Lake Wildlife Area. We acknowledge all colleagues and technicians at the Avian Science Center and Wildlife Biology Program at the University of Montana that supported data development. Views in this manuscript from United States Fish and Wildlife Service authors are their own and do not necessarily represent the views of the agency.

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