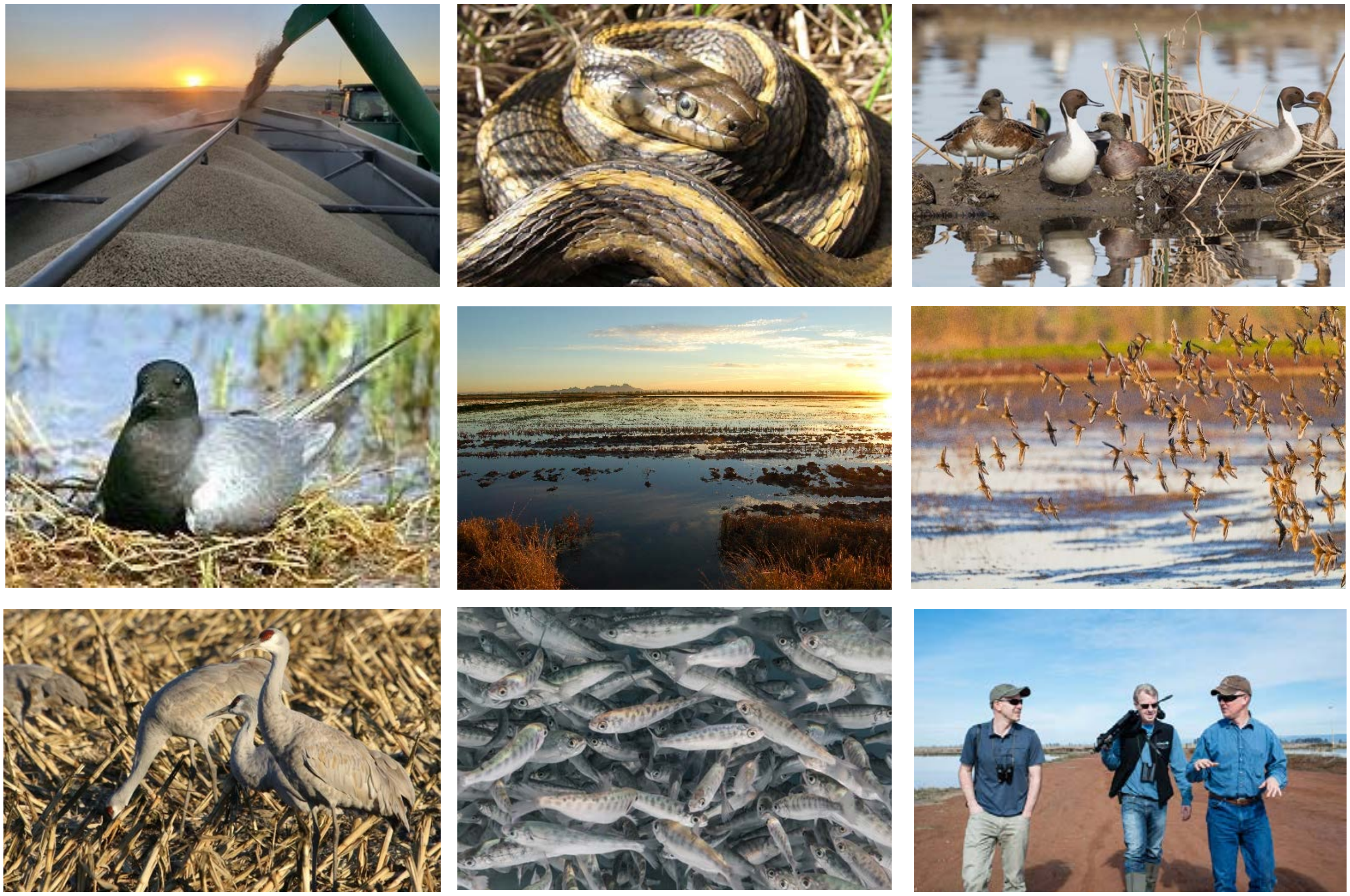
A Conservation Footprint for California Rice

Acres, locations, and management practices of ricelands to support multiple species of wildlife in the Central Valley, California



Report to the California Rice Commission

January 2025

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A partnership of the University of California Davis and Point Blue Conservation Science

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Recommended Citation:
Please cite individual section authors as:

[Authors]. 2025. [Section title] *in* J. M. Eadie and D. S. Karp (editors). *A Conservation Footprint for California Rice.* Report to the California Rice Commission. University of California, Davis, and Point Blue Conservation Science. Pages: 000-000.

Please cite the entire report as:

Eadie, John M., Daniel S. Karp, Francisco Bellido-Leiva, Lee R. Burrows, Kristen E. Dybala, Sean P. Fogenburg, Bruce A. Linquist, Andrew L. Rypel, Daniel A. Sumner, Brian D. Todd, Robert G. Walsh, Jessica Xu. 2025. *A Conservation Footprint for California Rice.* Report to the California Rice Commission. University of California, Davis, and Point Blue Conservation Science. 173 pages.

Cover photos: Top row: Rice harvest (Bruce Linquist); Giant Gartersnake (©Matt Meshriy, USGS; Northern Pintail (California Rice Commission); Middle row: Black Tern on nest (public domain); Sunrise over rice field (credit: Blake Barbaree/Point Blue); Sandhill Cranes (Daniel Karp); Bottom row: Shorebird flock (credit: Jak Wonderly Photography), Chinook salmon fry (credit: Jak Wonderly Photography); BirdReturns The Nature Conservancy (© Drew Kelly/TNC)

Acknowledgements

This project is a collaboration of the University of California Davis and Point Blue Conservation Science. Support for the project was provided by the California Rice Commission through a grant to the Center for Watershed Sciences UC Davis (A24-3761) and to Point Blue Conservation Science. Additional funding and support were provided by the Dennis G. Raveling Endowment UC Davis, U.S. Department of Agriculture National Institute of Food and Agriculture Hatch projects CA-D-WFB-6342-H (to JME), CA-D-WFB-2617-H (to BDT), USDA NIFACA-D-WFB-2716-CG (to DSK, ALR, JME). ALR was supported by a collaborative grant from the USDA NRCS and the California Rice Commission (CRC). Funds from the California Rice Commission included private matching gifts and additional support from Syngenta Corporation, the S.D. Bechtel, Jr. Foundation, Valent USA LLC, the California Rice Research Board, California Ricelands, Corteva agriscience, Agriform, AgriSource, Growers Ag. Service and the Northern California Water Association. ALR was also supported by the California Agricultural Experimental Station of the University of California Davis, grant number CA-D-WFB-2467-H and by the Peter B. Moyle and California Trout Endowment for Coldwater Fish Conservation.

We thank several individuals who helped immeasurable with analyses, data, and comments including Cory Overton, Dan Fehringer, Patrick Donnelly, Rob Blenk, Autumn Iverson, and Catherine Hickey.

Tim Johnson, Paul Buttner, and Kristin Sesser greatly facilitated the development of this project and provided helpful reviews. This is a working paper and represents research in progress. The report represents the opinions of the authors and is the product of professional research. It is not meant to represent the position or opinions of the California Rice Commission or any other agency, entity or staff who may have contributed ideas or information to this review.

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1. Executive Summary

- Rice agriculture, especially winter-flooded rice fields, provides surrogate wetlands that host a diversity of species in the Central Valley. Rice fields are critical for Giant Gartersnakes, wintering waterfowl, wintering and breeding shorebirds, Sandhill Cranes, native fishes, and many other species. However, uncertainties in climate, water availability, agricultural crop markets, and urban expansion are precipitating changes in management practices, increased variability and magnitude of fallowing, and, in some cases, crop conversion.

- These uncertainties raise several important questions for both the rice industry and wildlife conservation: (1) How much rice is needed to meet minimum requirements for species of conservation concern in the California Central Valley? (2) How much planted rice needs to be flooded in winter and/or managed in specific ways to continue providing ecological benefits? (3) Are there specific locations where rice is especially needed to maintain high levels of wildlife abundance and diversity? (4) Finally, in the face of continuing challenges to agricultural and managed wetland habitats, which management practices, or suites of practices, are economically feasible to implement and benefit the greatest number of species, without negatively impacting other species?

- This project represents an initial attempt to address these questions. We briefly review the agronomics, economics, and conversion risk of ricelands in the Central Valley of California. We first develop a single baseline mapping framework including multiple habitat components that could influence the abundance and distribution of various wildlife species. We then review the core needs of five key taxonomic groups (Giant Gartersnakes, wintering ducks, wintering and breeding shorebirds and Black Terns, Sandhill Cranes, and native fishes) with respect to ricelands. We go on to provide an estimate of the rice acreage, management actions, and locations that would be of greatest value to each group. We include an evaluation of the potential economic value of riceland habitats and wildlife to address potential social welfare gains from improved wildlife habitat populations. Finally, we synthesize key outcomes from our taxa-specific analyses to provide an evaluation of the rice footprint needed to support these taxonomic groups.

- In addition to providing nutritious and healthy food for millions, the California rice industry is central to the rural economy of the Sacramento Vally and more broadly. Rice production itself supports about $1 billion of added economic value and more than 7,500 jobs when at full production. Rice planted acreage over the past decade has been highly variable from 250,000 to 540,000 acres (100,000 to over 215,000 ha), primarily due to drought and wet springs. Where rice is planted, about 50% of the land is flooded during winter to aid in rice straw decomposition and provide habitat. Management of these fields varies tremendously. Under current conditions, we found that there is little risk of conversion of ricelands to other field crops. Although there has been some replacement by orchard crops, this is limited and has occurred on the outer margins of the rice area and along the rivers.

- We consolidated and updated multiple datasets to map habitat characteristics, spatial relationships, and temporal dynamics across the Central Valley. We used data from 2020 to 2024 to develop five distinct habitat scenarios representing a range of conditions, from favorable years with extensive rice planting (>500,000 rice acres in 2020/21 and 2023/24) to challenging years with reduced planting due to drought (~250,000 rice acres in 2022/23). This mapping effort provided the foundation for evaluating habitat needs across taxa.

- With the draining and loss of much historical wetland habitat, flooded rice now provides critical surrogate habitat for the protected Giant Gartersnake. The recovery plan for the species recognizes the importance of flooded rice to Giant Gartersnake populations and calls for >80,000 acres of flooded rice along with protecting wetlands as part of a recovery strategy. Priorities to sustain populations include ensuring consistent planting and flooding of rice in parcels close to remaining wetlands, especially when those parcels currently support gartersnakes, as well as identifying ways of enhancing habitat —especially in canals —through earlier water availability in late March to April each year.
- California's Central Valley serves as a vital wintering ground for millions of waterfowl along the Pacific Flyway. Flooded rice fields provide critical foraging habitat for waterfowl during winter. We used the SWAMP bioenergetic model to evaluate the amount and spatial distribution of rice acreage required to support duck population goals during the non-breeding season. At 300,000 acres of planted rice, population sizes experienced steep declines dropping below 50% of target goals by early January, lipid reserves declined rapidly by January, and average flight distances exceeded 8 km by late January, forcing ducks to travel farther to forage. Conversely, with 500,000 acres of planted rice, populations remained near 100% of the target until late February and lipid accumulation continued, with reserves peaking in mid-January and sustained through March. Spatial analyses identified high-priority rice fields for conservation, with projected high-use areas concentrated near refuges and managed wetlands.
- Rice serves important habitat to wetland-dependent birds year-round, including several shorebirds and nearly 100% of the Central Valley breeding habitat for Black Tern, a California Bird Species of Special Concern. A rice footprint of >426,043 ac (172,414 ha) is needed to maintain a Black Tern population above 1,000 individuals, reducing the risk of local extirpation and loss of genetic diversity. If habitat quality could be enhanced to restore breeding densities, a rice footprint of > 472,794 ac (191,333 ha) may be sufficient to meet the CVJV's long-term population objective for Black Tern, provided flooding is maintained throughout the entire breeding season. A rice footprint of this size would also contribute to maintaining a breeding Black-necked Stilt population and would continue to provide substantial breeding habitat for American Avocet.
- Rice provides more than half of the food energy supply needed to support the large, diverse community of shorebirds in the non-breeding season. For nonbreeding shorebirds, there were energy shortfalls during the fall and spring "shoulder" portions of every scenario that was explored. The rice footprint needed to support nonbreeding shorebirds depends on the extent that is winter-flooded, including winter-flooded fallow rice fields. A threshold for the midwinter peak of flooded rice and fallowed rice of 373,540 ac (151,167 ha) would support nonbreeding shorebird conservation objectives.
- The vast majority of California's Sandhill Cranes winter in the Sacramento Valley and the Yolo-Delta region, where they make substantial use of rice farms for both foraging (unflooded conditions) and roosting (flooded conditions). The Greater subspecies is state-listed as threatened and the Lesser subspecies as a species of special concern. To accommodate cranes at recommended roosting densities, an estimate of 43,139 acres of flooded rice is needed in November, the month of maximum abundance, to complement other potential roosting habitat. 56,759 acres (22,970 ha) would be needed if no other roosting habitat was available. A mix of shallowly flooded and unflooded rice would best

support cranes' needs for roosting and foraging habitat. Providing this habitat in the Yolo-Delta Region is a high priority because of high bird numbers and high roost suitability.

- California's native fish populations are in a clear state of decline, but there is high potential to utilize winter-flooded rice fields as fish habitat. Flood extension management of ricelands for fishes promotes opportunities for growth and survival, primarily due to robust densities of zooplankton that naturally develop on fields (the primary food source of many native fishes including juvenile salmon). Mathematical salmon population models developed specifically for this report clearly show that successful implementation of flood extension practices for fishes could massively improve adult salmon numbers. This analysis indicates that all the Yolo and Sutter bypass acres - 74,000 acres (29,947 ha), of which 30,000 acres (12,141 ha) is rice - would be needed to nearly double the population cohort replacement rate. That said, rice alone cannot provide enough habitat for stable populations of fishes. As such, other complementary management actions (e.g., managing rice for 'fish food'), funding, and collaboration are needed to fully recover fish populations.
- A wide range of methods and empirical sources document extensive economic support from society for wild species habitat. Applying this evidence to rice contexts suggests the economic value of rice farms as wildlife habitat may exceed hundreds of dollars per acre per year.
- Summarizing, our estimates of the planted rice acreage needed for these taxonomic groups include: 30,000 ac for native fishes (only Yolo and Sutter bypasses are considered in this report), 43,139 ac (Sandhill Cranes), 80,000 ac (Giant Gartersnake), 373,540 ac of winter-flooded rice and flooded fallow rice fields (non-breeding shorebirds), 472,794 ac of planted rice (to restore populations of Black Terns and support other breeding shore birds), and 500,000 ac (non-breeding ducks). A minimum rice footprint could be determined as that which satisfies the minimum needs of the species with the largest acreage requirement - any reduction of rice below that target would impact at least that one species. Under this premise, a minimum footprint of ~470,000– 500,000 acres would define the conservation footprint. We discuss several factors that will influence this estimate, and we consider a range of rice acreages where the amount of rice habitat is inadequate under all conditions (*high risk),* where there is risk of not meeting population objectives, especially when conditions are poor (*insufficient)*, and where there is enough rice habitat to buffer populations under almost all conditions (*sufficient*).
- We use our mapping analysis to identify rice locations that are high priority for multiple species. We emphasize that (1) these are not the only areas of conservation importance, (2) they are not weighted rankings of conservation value, and (3) they do not define the minimum footprint. Rather, we present these maps as tools for strategic conservation planning to identify focal areas where joint management may be most effective and/or where management tradeoffs for different species may occur.
- Finally, we identify research needs for each taxonomic group. We also describe next steps to develop a more refined rice conservation footprint using multi-objective decision analysis, expanding the species groups considered, enhancing economic and ecological data integration, as well as modelling and engaging stakeholders in key priority areas.

2. Introduction: A Need for Multi-species Conservation

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Historically, extensive seasonal wetlands shaped the ecology and biodiversity of California's Central Valley (Frayer et al. 1989, Sterling and Buttner 2011, Central Valley Joint Venture 2020). However, over 90% of Central Valley wetlands were drained for agriculture, flood control, and urbanization over last century, with severe consequences for Central Valley wildlife (Frayer et al. 1989, Sterling and Buttner 2011, Central Valley Joint Venture 2020). Fortunately, the emergence of rice agriculture, especially winter-flooded rice fields, created surrogate wetlands that now host an impressive diversity of species in the Central Valley, including globally-recognized spectacles of wildlife migration as well as several threatened and endangered species (Gilmer et al. 1982, Elphick and Oring 2003, Eadie et al. 2008, Elphick et al. 2010b, 2018, Shuford et al. 2019, Central Valley Joint Venture 2020, Casazza et al. 2021). Research and extensive monitoring by academic, government, industry, and NGO scientists in the Central Valley of California over the past several decades have documented numerous benefits of California rice to wildlife and the critical ecological functions and services that they provide (Table 2.1).

Table 2.1. Examples of research and ecological values provided by rice agriculture to wildlife.

Ecological Value of California Rice	**References (representative not exhaustive)**
Occurrence of over 230 species in rice fields	(California Rice Commission 2011, Sterling and Buttner 2011)
Value of flooded rice fields as winter habitat for waterfowl, shorebirds, wading birds, and cranes as well as breeding habitat for some of these species	(Brouder and Hill 1995, Reid and Heitmeyer 1995, Elphick and Oring 1998, Eadie et al. 2008, Petrie and Petrik 2010, Sesser et al. 2016, 2018, Elphick et al. 2018, Casazza et al. 2021, Conlisk et al. 2023)
Importance of rice fields for shorebirds during fall and winter migration	(Shuford et al. 1998, Elphick and Oring 1998, Hickey et al. 2003, Elphick and Oring 2003, Elphick 2008, Elphick et al. 2010b, Petrie and Petrik 2010, Dybala et al. 2017, Elphick et al. 2018, Matchett and Fleskes 2018)
Value of residual rice grain as a food source for waterfowl and other species	(Miller et al. 1989, Reid and Heitmeyer 1995, Fleskes and Perry 2005, Fleskes et al. 2012, Matthews et al. 2018)
Importance of rice fields to endangered reptiles such as Giant Gartersnake	(Halstead et al. 2010, 2014, 2019, Wylie et al. 2010, Sterling and Buttner 2011, U.S. Fish and Wildlife Service 2017)
Value of winter-flooded rice fields for production of invertebrate food resources, fueling rapid growth and survival by juvenile salmonids prior to seaward migration	(Jeffres et al. 2008, 2020, Moyle et al. 2011, Garnache 2015, Katz et al. 2017, Corline et al. 2017, Sommer et al. 2020, Holmes et al. 2021, Tallman 2024, Rossi et al. 2024)
Effect of different post-harvest methods/treatments on availability of waste grain and subsequent use by wildlife	(Miller et al. 1989, Day and Colwell 1998, Elphick and Oring 1998, Colwell and Taft 2000, Elphick and Oring 2003, Elphick 2004, Elphick et al. 2010b, Miller et al. 2010, Fleskes et al. 2012, Strum et al. 2014, Brogi et al. 2015, Sesser et al. 2018, 2018, Matthews et al. 2022a, Peterson et al. 2024, Conlisk et al. 2024)
Effect of drought and loss of flooded rice on observed and predicted wildlife populations	(Petrie et al. 2016, Reiter et al. 2018a, Halstead et al. 2019, Byrd et al. 2020, Matchett 2021, Kahara et al. 2022)
Bioenergetic modeling and scenario evaluation to evaluate and project consequences of changes in winter-flooded rice	(Petrie et al. 2016, Dybala et al. 2017, Central Valley Joint Venture 2020, Matchett 2021)
Analyses of the agronomic value of winter-flooding for growers, opportunities, and limitations of winter-flooding and post-harvest management to benefits wildlife	(Day and Colwell 1998, Elphick 2000, Fitzgerald et al. 2000, Bird et al. 2000, Garr 2002, Elphick and Oring 2003, Van Groenigen et al. 2003, Anders et al. 2008, Brogi et al. 2015)

Unquestionably, rice agriculture plays a significant role in providing food resources and habitat to many species of California native birds, reptiles, amphibians, and fishes. Winter-flooded rice fields, in particular, are critical for wintering waterfowl and shorebirds (Table 1.1). Indeed, it is estimated that residual rice grain and benthic invertebrates in winter-flooded rice fields provide over half of all food energy resources needed by these species during the non-breeding season (Central Valley Joint Venture 2006a, 2020). Countless other waterbirds (*e.g.,* cranes, terns, herons and egrets) likewise depend heavily on rice fields for nesting, foraging, and/or roosting throughout the year. Rice fields are also playing an increasingly important role in fish and reptile conservation, including endangered salmonids (Katz et al. 2017, Holmes et al. 2021, Rossi et al. 2024) and the Giant Gartersnake (Halstead et al. 2010, 2019, U.S. Fish and Wildlife Service 2017).

The effects of rice agriculture on California wildlife cascade to positively impact people. Indeed, California rice agriculture is not only a large and economically important agricultural commodity, it also provides myriad recreational opportunities for birdwatchers, hunters, and outdoor enthusiasts (Petrie et al. 2014b, Matthews and Sumner 2024). Leasing of hunting access can, in turn, be an important source of supplemental income for many rice farmers (Matthews 2019).

Yet many questions and challenges remain for the rice industry and the wildlife that depend on it. Specifically, uncertainties in climate, water availability, agricultural crop markets, and urban expansion are precipitating changes in management practices, increased variability and magnitude of fallowing, and, in some cases, crop conversion that may together have important consequences for Central Valley wildlife, not to mention the benefits that those wildlife provide to people (Elphick et al. 2010a, Stralberg et al. 2011, Joyce et al. 2011, Strum et al. 2013, Matthews 2019, Kahara et al. 2022, Donnelly et al. 2022, Conlisk et al. 2023, Peterson et al. 2024). There are also emerging questions and potential conflicts over novel wildlife conservation practices in ricelands; for example, changes in the timing, duration, and depths of fall, winter, and spring flooding that may benefit some species but harm others. In sum, despite the many ecological benefits of rice agriculture, uncertainty remains as to whether current acreage under current management practices will be sufficient to sustain California's Central Valley wildlife populations into the future.

Together, these uncertainties raise several important questions for both the rice industry and wildlife conservationists. First, how much rice is needed to meet minimum requirements for flagship species and species of conservation concern in the California Central Valley, both now and into the future? Second, of all the planted rice, how much needs to be flooded in winter and/or managed in specific ways to continue providing ecological benefits? Third, are there specific locations where rice is especially needed to maintain high levels of wildlife abundance and diversity? Finally, in the face of continuing challenges to agricultural and managed wetland habitats, which management practices, or suites of practices, are economically feasible to implement and benefit the greater number of species, without negatively impacting other species?

This project represents an initial attempt to address these questions. While many studies have examined the value of rice habitat to specific groups of wildlife species (Table 1), few have done so in an integrated fashion – evaluating the benefits, constraints, and tradeoffs for multiple wildlife species simultaneously. This is a much more challenging task, requiring a synthesis of the ecological, agronomic, economic, and management influences on multiple taxonomic groups as well as a synthetic evaluation of potential mutual benefits or tradeoffs. In the following report, we provide a review of the key issues facing several groups of wildlife that depend on rice fields. We then consider the needs of each group in terms of (i) the amount of rice needed, (ii) management practices on those fields that are most beneficial, and (iii) locations within the Central Valley that might have the greatest value for conservation. In doing so, we develop a footprint of the rice acreage needed to sustain multiple species of wildlife using ricelands in California. We refer to this as a “muddy footprint” because the complexity of such an undertaking precludes an exact accounting of the necessary acreage to support such diverse taxa. Instead, our goal was simply to provide an initial scoping of the acreage of rice and types of management that may be required. Future work would require sophisticated analyses that enable formal valuation of the habitat needs and ecosystem services provided by different taxa as well as evaluation of alternative habitat and policy allocations (Elphick 2004, Zhang et al. 2007, Kremen and Miles 2012, Sundar and Kittur 2013, Garnache 2015, Suddeth and Lund 2016, Kremen and Merenlender 2018, Chivenge et al. 2019, Dang et al. 2019, Ahmed et al. 2020, Lorenzón et al. 2020, Liu et al. 2020a, 2020b, Gao et al. 2023). Accordingly, our analyses at this stage are intended for general guidance rather than precise prescription or policy recommendations. Nonetheless, our analysis provides a first integrated evaluation of the needs of multiple species and, in doing so, provides a baseline footprint of the ‘key rice acres’ that may be most valuable for conservation purposes in the Central Valley.

In this first iteration of the “muddy footprint”, we evaluated the role of rice in supporting several key taxonomic groups: Giant Gartersnake, waterfowl, shorebirds, Black Tern, Sandhill Crane, and salmon. This list is not comprehensive of all species that rely on ricelands as habitat throughout the year, including other birds, amphibians, and invertebrates, and in some cases our analyses were limited to only one season. For example, we evaluated wintering waterfowl but we did not have the analytical framework to consider breeding waterfowl. These additional seasons and species should be considered in future analyses. This initial set of taxonomic groups were most suitable for an initial synthesis because all are species of important conservation and management concern in California, all depend on ricelands for some or all their annual cycle, and there is sufficient research on each group to enable analysis.

To set our analyses in context, we begin by briefly reviewing the agronomics, economics, and conversion risk of ricelands in the Central Valley of California (Section 3). Because our analysis is necessarily spatially explicit, we then discuss our strategy for developing a single baseline mapping framework that included flooded and dry rice, other crops, managed wetlands, and other habitat components that could influence the abundance and distribution of various wildlife species (Section 4). Next, we review the core needs for each taxonomic group with respect to ricelands and provide an estimate of the rice acreage, management actions, and locations that would be of greatest value to each group (Section 5). We then include an evaluation of the potential economic value of riceland habitats and wildlife to attempt to address the social welfare gains from improved wildlife habitat populations and the potential for support for costly measures to maintain such habitat contribution in California rice fields (Section 6).

Finally, and most importantly, we synthesize and distill key outcomes from our taxa-specific analyses (Section 7). We first discuss the compatibility of current and emerging rice management practices; for example, which management practices are vital for each species and do they present tradeoffs for managing multiple species simultaneously? Second, we assess priority rice locations; for example, which rice field locations within the valley provide the greatest benefits to the most species? Third, and finally, we provide a rough estimate of a rice acreage footprint that is needed to sustain desired wildlife species and populations within a viable rice production industry.

Many sections were written so that they could stand alone with their own figures, tables, appendices, and references to allow readers to focus on that element of the report. Accordingly, sections are relatively short (5-10 pages of text), but are intended to be thorough and technical, often with accompanying appendices. A highlights section is included at the beginning of each section to emphasize the key results. That said, we encourage readers to consider the report in its entirety. This highly interdisciplinary effort engaged scientists and researchers with deep and distinct histories and expertise in their focal areas. There have been few similar attempts to integrate and synthesize across multiple taxonomic groups and management components at such a scale for an agricultural industry in California.

References

Ahmed, N., S. Thompson, B. Hardy, and G. M. Turchini. 2020. An ecosystem approach to wild rice-fish cultivation. Reviews in Fisheries Science and Aquaculture.

Anders, M. M., C. Van Kessel, and J. M. Eadie. 2008. Agronomic Impacts of Winter Wetland and Waterfowl Management in Ricelands. Page Conservation in Ricelands of North America. The Rice Foundation, Stuttgart, Arkansas.

Bird, J. A., G. S. Pettygrove, and J. M. Eadie. 2000. The impact of waterfowl foraging on the decomposition of rice straw: mutual benefits for rice growers and waterfowl. Journal of Applied Ecology 37:728–741.

Brogi, A., C. A. Pernollet, M. Gauthier-Clerc, and M. Guillemain. 2015. Waterfowl foraging in winter-flooded ricefields: Any agronomic benefits for farmers? Ambio 44:793–802.

Brouder, S., and J. Hill. 1995. Conjunctive use of farmland adds value: Winter flooding of ricelands provides waterfowl habitat. California Agriculture 49:58–64.

Byrd, K. B., A. A. Lorenz, J. A. Anderson, C. S. A. Wallace, K. A. Moore-O'Leary, J. Isola, R. Ortega, and M. E. Reiter. 2020. Quantifying drought's influence on moist soil seed vegetation in California's Central Valley through remote sensing. Ecological Applications 30:e02153.

California Rice Commission. 2011. Wildlife Known To Use California Ricelands - Species list. Page Species List.

Casazza, M. L., F. McDuie, S. Jones, A. A. Lorenz, C. T. Overton, J. Yee, C. L. Feldheim, J. T. Ackerman, and K. M. Thorne. 2021. Waterfowl use of wetland habitats informs wetland restoration designs for multi-species benefits. Journal of Applied Ecology 58:1910–1920.

Central Valley Joint Venture. 2006. Central Valley Joint Venture 2006 Implementation Plan: Conserving Bird Habitat. U.S. Fish & Wildlife Service, Sacramento, California.

Central Valley Joint Venture. 2020. Central Valley Joint Venture 2020 Implementation Plan. U.S& Wildlife Service, Sacramento, CA.

Chivenge, P., O. Angeles, B. Hadi, C. Acuin, M. Connor, A. Stuart, R. Puskur, and S. Johnson-Beebout. 2019. Ecosystem services in paddy rice systems. Pages 181–201 The Role of Ecosystem Services in Sustainable Food Systems. Elsevier.

Colwell, M. A., and O. W. Taft. 2000. Waterbird communities in managed wetlands of varying water depth. Waterbirds 23:45–55.

Conlisk, E. E., K. B. Byrd, E. Matchett, A. A. Lorenz, M. Casazza, G. H. Golet, M. D. Reynolds, K. A. Sesser, and M. E. Reiter. 2023. Changes in habitat suitability for wintering dabbling ducks during dry conditions in the Central Valley of California. Ecosphere 14:e4367.

Conlisk, E. E., G. H. Golet, M. Reynolds, N. Elliott, and M. E. Reiter. 2024. Factors influencing shorebird use of post-harvest flooded rice fields in California's Sacramento Valley. The Journal of Wildlife Management 88:e22661.

Corline, N. J., T. Sommer, C. A. Jeffres, and J. Katz. 2017. Zooplankton ecology and trophic resources for rearing native fish on an agricultural floodplain in the Yolo Bypass California, USA. Wetlands Ecology and Management 25:533–545.

Dang, K. B., W. Windhorst, B. Burkhard, and F. Müller. 2019. A Bayesian belief network – based approach to link ecosystem functions with rice provisioning ecosystem services. Ecological Indicators 100:30–44.

Day, J. H., and M. A. Colwell. 1998. Waterbird communities in rice fields subjected to different post-harvest treatments. Waterbirds 21:185–197.

Donnelly, J. P., J. N. Moore, M. L. Casazza, and S. P. Coons. 2022. Functional Wetland Loss Drives Emerging Risks to Waterbird Migration Networks. Frontiers in Ecology and Evolution 10:844278.

Dybala, K. E., M. E. Reiter, C. M. Hickey, W. D. Shuford, K. M. Strum, and G. S. Yarris. 2017. A bioenergetics approach to setting conservation objectives for non-breeding shorebirds in California's Central Valley. San Francisco Estuary and Watershed Science 15.

Eadie, J., C. Elphick, K. Reinecke, and M. Miller. 2008. Wildlife values of North American ricelands. Pages 7–90 Conservation in Ricelands of North America: Current State of Our Knowledge and a Course for Future Research and Education. The Rice Foundation, Stuttgart, AR.

Elphick, C. 2000. Functional equivalency between rice fields and seminatural wetland habitats. Conservation Biology 14:181–191.

Elphick, C. 2008. Landscape effects on waterbird densities in california rice fields: taxonomic differences, scale-dependence, and conservation implications. Waterbirds 31:62–69.

Elphick, C., P. Baicich, K. C. Parsons, M. Fasola, and L. Mugica. 2010a. The future for research on waterbirds in rice fields. Waterbirds 33:231–243.

Elphick, C., T. R. Kelsey, Hickey, Catherine, P. Buttner, Strum, Khara, and Iglecia, Monica. 2018. Wetland bird conservation in california rice fields. Pages 293–296 Cranes and Agriculture: A Global Guide For Sharing The Landscape. Minuteman Press, Baraboo, Wisconsin.

Elphick, C., and L. W. Oring. 2003. Conservation implications of flooding rice fields on winter waterbird communities. Agriculture, Ecosystems & Environment 94:17–29.

Elphick, C. S. 2004. Assessing conservation trade-offs: identifying the effects of flooding rice fields for waterbirds on non-target bird species. Biological Conservation 117:105–110.

Elphick, C. S., and L. W. Oring. 1998. Winter management of Californian rice fields for waterbirds. Journal of Applied Ecology 35:95–108.

Elphick, C., O. Taft, and P. M. Loureno. 2010b. Management of rice fields for birds during the non-growing season. Waterbirds 33:181–192.

Fitzgerald, G. J., K. M. Scow, and J. E. Hill. 2000. Fallow season straw and water management effects on methane emissions in California rice. Global Biogeochemical Cycles 14:767–776.

Fleskes, J. P., B. J. Halstead, M. L. Casazza, P. S. Coates, J. D. Kohl, and D. A. Skalos. 2012. Waste Rice Seed in Conventional and Stripper-Head Harvested Fields in California: Implications for Wintering Waterfowl. Journal of Fish and Wildlife Management 3:266–275.

Fleskes, J. P., and W. M. Perry. 2005. Change in area of winter-flooded and dry rice in the northern central valley of California determined by satellite imagery. Califonia Fish and Game 91:207–215.

Frayer, W. E., D. D. Peters, H. R. Pywell, and W. R. Pywell. 1989. Wetlands of the california central valley: status and trends, 1939 to mid-1980's.

Gao, H., L. Dai, Q. Xu, P. Gao, and Z. Dou. 2023. Transforming agrifood systems in a win–win for health and environment: evidence from organic rice–duck coculture. Journal of the Science of Food and Agriculture 103:968–975.

Garnache, C. 2015. Fish, farmers, and floods: Coordinating institutions to optimize the provision of ecosystem services. Journal of the Association of Environmental and Resource Economists 2:367–399.

Garr, J. 2002. Rice enhancement project annual report. Rancho Cordova, CA.

Gilmer, D. S., M. R. Miller, R. D. Bauer, and J. R. Ledonne. 1982. California's Central Valley Wintering Waterfowl: Concerns and Challenges California's Central Valley Wintering Waterfowl: Concerns and Challenges. US Fish & Wildlife Publications. 41.

Halstead, B. J., J. P. Rose, G. A. Reyes, G. D. Wylie, and M. L. Casazza. 2019. Conservation reliance of a threatened snake on rice agriculture. Global Ecology and Conservation 19:00681.

Halstead, B. J., G. D. Wylie, and M. L. Casazza. 2010. Habitat suitability and conservation of the giant gartersnake (Thamnophis gigas) in the Sacramento valley of California. Copeia:591–599.

Halstead, B. J., G. D. Wylie, and M. L. Casazza. 2014. Ghost of habitat past: historic habitat affects the contemporary distribution of giant garter snakes in a modified landscape. Animal Conservation 17:144–153.

Hickey, C. M., G. W. Page, W. D. Shuford, and S. Warnock. 2003. Southern Pacific Shorebird Conservation Plan: A strategy for supporting California's Central Valley and coastal shorebird populations. Stinson Beach, California.

Holmes, E. J., P. Saffarinia, A. L. Rypel, M. N. Bell-Tilcock, J. V. Katz, and C. A. Jeffres. 2021. Reconciling fish and farms: Methods for managing California rice fields as salmon habitat. PLoS ONE 16:e0237686.

Jeffres, C. A., E. J. Holmes, T. R. Sommer, and J. V. E. Katz. 2020. Detrital food web contributes to aquatic ecosystem productivity and rapid salmon growth in a managed floodplain. PLoS ONE 15.

Jeffres, C. A., J. J. Opperman, and P. B. Moyle. 2008. Ephemeral floodplain habitats provide best growth conditions for juvenile Chinook salmon in a California river. Environmental Biology of Fishes 83:449–458.

Joyce, B. A., V. K. Mehta, D. R. Purkey, L. L. Dale, and M. Hanemann. 2011. Modifying agricultural water management to adapt to climate change in California's central valley. Climatic Change 109:299–316.

Kahara, S. N., D. Skalos, B. Madurapperuma, and K. Hernandez. 2022. Habitat quality and drought effects on breeding mallard and other waterfowl populations in California, USA. The Journal of Wildlife Management 86:e22133.

Katz, J. V. E., C. Jeffres, J. L. Conrad, T. R. Sommer, J. Martinez, S. Brumbaugh, N. Corline, and P. B. Moyle. 2017. Floodplain farm fields provide novel rearing habitat for Chinook salmon. PLoS ONE 12.

Kremen, C., and A. M. Merenlender. 2018. Landscapes that work for biodiversity and people. Science 362:eaau6020.

Kremen, C., and A. Miles. 2012. Ecosystem services in biologically diversified versus conventional farming systems: benefits, externalities, and trade-offs. Ecology and Society 17:40.

Liu, D., R. Tang, J. Xie, J. Tian, R. Shi, and K. Zhang. 2020a. Valuation of ecosystem services of rice–fish coculture systems in Ruyuan County, China. Ecosystem Services 41:101054.

Liu, X., B. R. Bakshi, B. Rugani, D. M. de Souza, J. Bare, J. M. Johnston, A. Laurent, and F. Verones. 2020b. Quantification and valuation of ecosystem services in life cycle assessment: Application of the cascade framework to rice farming systems. Science of the Total Environment 747:141278.

Lorenzón, R. E., E. J. León, M. Juani, A. H. Beltzer, P. M. Peltzer, R. C. Lajmanovich, and A. M. Attademo. 2020. Can agroecological management increase functional diversity of birds in rice fields? Revista de Biologia Tropical 68:873–883.

Matchett, E. L. 2021. Using High Resolution Satellite and Telemetry Data to Track Flooded Habitats, Their Use by Waterfowl, and Evaluate Effects of Drought on Waterfowl and Shorebird Bioenergetics in California. Open-File Report.

Matchett, E. L., and J. P. Fleskes. 2018. Waterbird Habitat in California's Central Valley Basins Under Climate, Urbanization, and Water Management Scenarios. Journal of Fish and Wildlife Management 9:75–94.

Matthews, L. 2019. Changing post-harvest practices, impacts on waste grain availability, and growers perspectives. Masters Thesis., University of California Davis, Davis, California, USA.

Matthews, L. J., M. Petrie, and J. M. Eadie. 2018. Impacts of Changing Post-harvest Agricultural Practices on Waste Grain Availability in California's Central Valley. Page Manuscript to be submitted to the Journal of Fish & Wildlife Management.

Matthews, L. J., M. Petrie, and J. M. Eadie. 2022. Impacts of Changing Postharvest Agricultural Practices on Abundance of Waste Grain in California's Central Valley. Journal of Fish and Wildlife Management 13:320–333.

Matthews, W., and D. Sumner. 2024. Contributions of the California Rice Industry to the California Economy. University of California Davis.

Miller, M. R., J. D. Garr, and P. S. Coates. 2010. Changes in status of harvested rice fields in the. implications for wintering waterfowl. Wetlands 30:939–947.

Miller, M. R., D. E. Sharp, D. S. Gilmer, and D. Mulvaney. 1989. Rice Available To Waterfowl In Harvested Fields In The Sacramento Valley, California. California Fish and Game 75:113–123.

Moyle, P. B., J. V. E. Katz, and R. M. Quiñones. 2011. Rapid decline of California's native inland fishes: A status assessment. Biological Conservation 144:2414–2423.

Peterson, S. H., J. T. Ackerman, C. R. Schacter, C. A. Hartman, and M. P. Herzog. 2024. Bird habitat value and management priorities of the California Winter Rice Habitat Incentive Program. San Francisco Estuary and Watershed Science 22.

Petrie, M., M. Brasher, and D. James. 2014. Estimating the biological and economic contributions that rice habitats make in support of North American Waterfowl. The Rice Foundation, Stuttgart, Arkansas, USA.

Petrie, M. J., J. P. Fleskes, M. A. Wolder, C. R. Isola, G. S. Yarris, and D. A. Skalos. 2016. Potential effects of drought on carrying capacity for wintering waterfowl in the central valley of california. Journal of Fish and Wildlife Management 7:408–422.

Petrie, M. J., and K. L. Petrik. 2010. Assessing waterbird benefits from water use in California Ricelands:12.

Reid, F., and M. Heitmeyer. 1995. Sidebar: Waterfowl and rice in California's Central Valley. California Agriculture 49:62–62.

Reiter, M. E., N. K. Elliott, D. Jongsomjit, G. H. Golet, and M. D. Reynolds. 2018. Impact of extreme drought and incentive programs on flooded agriculture and wetlands in California's Central Valley. PeerJ 6:e5147.

Rossi, G. J., J. R. Bellmore, J. B. Armstrong, C. Jeffres, S. M. Naman, S. M. Carlson, T. E. Grantham, M. J. Kaylor, S. White, J. Katz, and M. E. Power. 2024. Foodscapes for salmon and other mobile consumers in river networks. BioScience 74:586–600.

Sesser, K. A., M. Iglecia, M. E. Reiter, K. M. Strum, C. M. Hickey, R. Kelsey, and D. A. Skalos. 2018. Waterbird response to variable-timing of drawdown in rice fields after winter-flooding. PLOS ONE 13:e0204800.

Sesser, K. A., M. E. Reiter, D. A. Skalos, K. M. Strum, and C. M. Hickey. 2016. Waterbird response to management practices in rice fields intended to reduce greenhouse gas emissions. Biological Conservation 197:69–79.

Shuford, W. D., G. W. Page, and J. E. Kjelmyr. 1998. Patterns and dynamics of shorebird use of California's Central Valley. Condor 100:227–244.

Shuford, W. D., M. Reiter, K. Sesser, C. Hickey, and G. Golet. 2019. The Relative Importance of Agricultural and Wetland Habitats to Waterbirds in the Sacramento–San Joaquin River Delta of California. San Francisco Estuary and Watershed Science 17.

Sommer, T., B. Schreier, J. L. Conrad, L. Takata, B. Serup, R. Titus, C. Jeffres, E. Holmes, and J. Katz. 2020. Farm to fish: Lessons from a multi-year study on agricultural floodplain habitat. San Francisco Estuary and Watershed Science 18:1–20.

Sterling, J., and P. Buttner. 2011. Wildlife Known To Use California Ricelands. Third. California Rice Commission, Sacramento, California.

Stralberg, D., D. R. Cameron, M. D. Reynolds, C. M. Hickey, K. Klausmeyer, S. M. Busby, L. E. Stenzel, W. D. Shuford, and G. W. Page. 2011. Identifying habitat conservation priorities and gaps for migratory shorebirds and waterfowl in California. Biodiversity and Conservation 20:19–40.

Strum, K. M., M. E. Reiter, C. A. Hartman, M. N. Iglecia, T. R. Kelsey, and C. M. Hickey. 2013. Winter management of California’s rice fields to maximize waterbird habitat and minimize water use. Agriculture, Ecosystems & Environment 179:116–124.

Strum K. M., Sesser K., and Iglecia M. N. 2014. Waterbird Habitat Enhancement Program: Bird-friendly farming in California rice fields. California Rice Commission.

Suddeth, R., and J. Lund. 2016. Multi-Purpose Optimization for Reconciliation Ecology on an Engineered Floodplain--Yolo Bypass, California, USA. San Francisco Estuary and Watershed Science 14.

Sundar, K. S. G., and S. Kittur. 2013. Can wetlands maintained for human use also help conserve biodiversity? Landscape-scale patterns of bird use of wetlands in an agricultural landscape in north India. Biological Conservation 168:49–56.

Tallman, R. L. 2024. Outmigration Survival of Juvenile Chinook Salmon in Reconciled Ecosystems. UC Davis.

U.S. Fish and Wildlife Service. 2017. Recovery Plan for the Giant Garter Snake (Thamnophis gigas). U.S. Page 71 Fish and Wildlife Service, Pacific Southwest Region. Sacramento, California.

Van Groenigen, J. W., E. G. Burns, J. M. Eadie, W. R. Horwath, and C. Van Kessel. 2003. Effects of foraging waterfowl in winter flooded rice fields on weed stress and residue decomposition. Agriculture, Ecosystems & Environment 95:289–296.

Wylie, G. D., M. L. Casazza, C. J. Gregory, and B. J. Halstead. 2010. Abundance and Sexual Size Dimorphism of the Giant Gartersnake (Thamnophis gigas) in the Sacramento Valley of California. Journal of Herpetology 44:94–103.

Zhang, W., T. H. Ricketts, C. Kremen, K. Carney, and S. M. Swinton. 2007. Ecosystem services and dis-services to agriculture. Ecological Economics 64:253–260.

3. California Rice Agronomics, Economics, and Conversion Risk

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Highlights

- Rice planted acreage over the past decade has been highly variable at 250,000 to 540,000 acres (100,000 to over 215,000 ha). This is due to drought and wet springs with farmers claiming Prevented Planting insurance.
- In years when rice is not grown, the land is typically fallowed. Over the last decade, about 10% of riceland was fallowed each year.
- Rice farming contributes about $1 billion per year and about 7,000 jobs to the economy of the Sacramento Valley. These estimates do not include the economic value of the contributions to wildlife to people that is highlighted in other sections of this report.
- Where rice is planted, about 50% of the land is flooded during the winter, usually to aid in rice straw decomposition and provide habitat. How these fields are managed varies tremendously.
- The amount of flooding depends on cost and availability of water which varies annually and regionally.
- Under current conditions, there is little risk of conversion of most ricelands to other field crops, including hay or grains. Soils and likely revenues make this uneconomical.
- There has been some riceland replacement by orchard crops (mostly almond and walnuts). This land use change is limited and has occurred on the outer margins of the rice area and along the rivers. Heavy clay soils that make up much of the rice area, will limit further replacement.

3.1 Historical context

Rice production in California began in the early 1900's, with Chinese migrants first growing rice. The main region where rice first took hold commercially was in the Richvale area of Butte County. Rice production statistics were first collected in 1912. Through 1955, rice yields were between 21 and 36 cwt/ac (Appendix A.1, Figure 3.1). From the 1950s there was a steady increase in yield to 85 cwt/ac in 1992. Since 1992, yields have continued to increase but at a much slower pace, with the highest California average yields achieved in 2022 (when about half of typical acreage was planted) at 90.5 cwt/ac. Acreage was around 600 acres in 1912 but quickly increased to over 150,000 by 1920 (Figure 3.1). From 1940 to 1981 acreage increased to 600,000 acres. Since then, acreage has fluctuated between 600,000 (1981) and 256,000 (2022). The last decade has been a period of high variability in rice acreage. This variability is the result of two primary factors. First, drought and water availability. In years where water is limited, rice acres are reduced either due to a total lack of

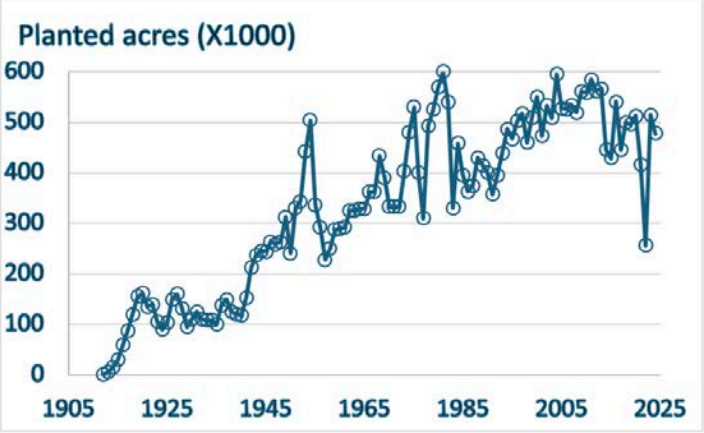

Figure 3.1: California rice acreage since 1912-2024.

water or rice farmers find it economically viable to sell their water to other farmers (often farmers with higher value crops or orchards). Secondly, farmers can claim insurance indemnities through the USDA Prevented Planting program. Farmers typically claim this when spring rainfall (usually in late April and May) prevent farmers from planting before June 1. When rice is not planted, fields are typically fallowed.

From 2008 to 2013, the number of fallowed acres ranged from 25,000 to 50,000 acres (Figure 3.2). In contrast, from 2014 to 2021, the number of fallowed acres was much greater ranged from 45,000 to 160,000 acres. Not shown in Figure 3.2 is 2022, where about 250,000 acres were fallowed due to drought. A lack of scheduled deliveries of irrigation water during the growing season, which is often known by early spring, is a source of insurable loss under the prevented planting provisions of USDA crop insurance.

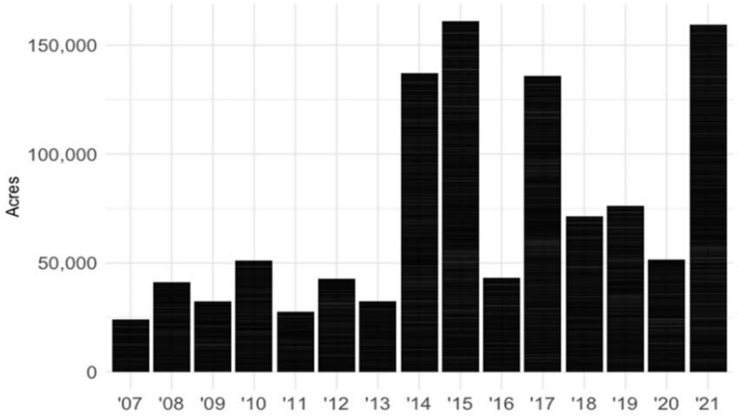

Figure 3.2: Amount of rice area fallowed from 2007-2021. (1 ac= 0.41 ha)

3.2 Rice industry economics

The California rice industry is large, dynamic, and closely linked to other parts of agriculture and the California economy. California accounts for close to three-quarters of U.S. short and medium-grain rice and all the U.S. *japonica* rice production. The rice produced in California is also processed here, and all the rice processed in California is produced on California rice farms. Thus, the direct economic contributions of the California rice industry include both rice farming and processing. After processing, most of California rice production is shipped out of California. Almost 40% is consumed in other parts of the United States and about half is exported.

As noted, California rice production and prices have been remarkably variable in recent years, related mainly to water availability. After 517,000 acres in 2020, planting declined to 407,000 acres in 2021, and collapsed to 252,000 acres in 2022, before recovering to 512,000 acres in 2023 and 485,000 acres in 2024. Because of demand sensitivity, farm prices move inversely with acreage and production. The average farm price for the 2020/21 marketing year (*i.e.,* the marketing of rice produced in 2020) was $22.60 per hundredweight. That price rose to $31.90 for 2021/22 and jumped further to $40.90 for the 2022/23 marketing year. USDA estimates that the average farm price in the 2023/24 and 2024/25 marketing years will be $22 per hundredweight. The direct revenue of California rice production (quantity times average price) for recent years are shown in the top row of Table 3.1.

Table 3.1: Contributions to California's Economy Including Value Added and Jobs.

	2020-21	2021-22	2022-23	2023-24	2024-25
Direct Farm Revenue ($ million)	993	1,153	886	954	923
Contributions to Value Added (Gross State Product)					
Direct Farm ($ million)	516	599	460	495	479
Indirect ($million)	300	348	267	288	279
Induced ($ million)	200	232	178	192	186
Full Effect ($ million)*	1,016	1,179	906	975	944
Contributions to Employment					
Direct Farm Jobs	2,343	2,719	2,089	2,250	2,176
Indirect Jobs	2,789	3,238	2,488	2,679	2,591
Induced Jobs	1,529	1,774	1,363	1,468	1,420
Approximate Full Effect*	6,660	7,731	5,940	6,397	6,188

Source: IMPLAN data and calculations supplemented with additional projections and model results. *Does not include contributions of rice million and post milling transport.

Rice production supports indirect and induced economic activity. Indirect effects include those generated by purchases of inputs, including services, from other industries. For rice, such purchases include fertilizer, pesticides, legal services, packing, and fuel. Induced impacts include the spending of income earned by farm employees, farmers, managers, and others within the rice industry. This income generates economic activity in many other industries such as local retail stores, schools, and local services. Such additional activities ripple through the California economy generating additional economic activity. In addition, California rice supports the rice processing and exporting sector. The full multiplier effects of rice milling and other post-farm-sale processing are not included in these estimates.

Our detailed rice-specific data and model of economic linkages (IMPLAN) demonstrates linkages from the rice industry to the rest of the California economy. It also measures how rice farming contributed to income and jobs throughout the economy for the crop years 2020/21 through projections for 2023/24, for which final pool prices are not yet established, and 2024/25, for which harvest is completed but marketing of the crop just beginning. After low production in 2021 and a severe drought in 2022, the California rice industry recovered production in 2023, but prices fell by enough to leave revenue in 2023/24 marketing year only slightly higher than in 2022/23. If prices stay low, the 2024/25 marketing year will be no better.

Table 3.1 shows the direct economic value added, which includes returns labor, management, and related resources. The California rice industry's full contribution to California value added has been between about $1.179 billion and $906 million in recent years. Besides generating income, the rice industry contributes jobs to the California economy. Our modeling and data measure all employment, including full-time year-round jobs as well as part-time or seasonal jobs. The employment numbers include between 2,919 direct jobs within rice farming and 7,731 jobs which includes the indirect and induced impacts. In addition, another approximately 3,000 jobs are in rice milling and exporting.

The main service of the California rice industry is to supply safe, nutritious, and enjoyable rice products to consumers here in California, the rest of the United States, and throughout the world. Besides these clear economic contributions to the California economy, the California rice industry contributes to ecological services and wildlife habitat that will be discussed below. Such benefits are difficult to quantify in economic terms, but California residents, among others, place considerable value on the habitat and ecosystem services that California rice provides. As described in section 6.

3.3 Rice management

Rice management varies widely among farmers. However, "typical" management in California is as follows. Most California rice is a water-seeded system. Water-seeding is rare outside California, although it is practiced on a small amount of acreage in Louisiana and Australia. Water-seeding is a form of direct seeding (as opposed to transplanting which is common in Asia). The practice involves doing all land preparation first, then flooding and planting aerially by broadcasting seed over the field. These fields are then maintained in a flooded state until about three weeks before harvest when fields are drained. During this flooded period there may be short times where water is drained or allowed to subside for brief periods to assist in crop establishment or as part of weed/herbicide management. Planting is typically done in late April through May. Averaged across years, May 12 is when 50% of rice is planted (USDA). Rice planting is often done earliest in Glenn and Colusa counties. Harvesting begins in early-September and continues through October. Harvest is done usually with a conventional combine header, although stripper headers are sometimes used. Following harvest, straw is usually chopped and disced into the soil to encourage straw decomposition. Many of the fields with in-field straw decomposition are flooded. The flooding of fields usually begins in November, with fields being drained in February. Soils are allowed to dry out and farmers will typically begin field operations in late March or early April depending on rain and soil conditions.

Various economic pressures, abiotic constraints, and/or conservation programs may alter these practices. For example, some fields may be flooded earlier or drained later to provide shorebird habitat. Similarly, to produce zooplankton for native fish, some fields are filled and drained multiple times during the winter. Indeed, there exists a substantial amount of variation in management that can affect rice acreage, winter flooding, and ecosystem services provided by the system. These include:

Fallow: As mentioned earlier, riceland is often fallowed. Fields that are fallowed during the summer are much less likely to be flooded during the following winter. Also, even if flooded, their value as wildlife/waterfowl habitat can be very different, as there is no rice straw residues/grain. Fields that are fallowed tend to be spatially random. However, during the drought year of 2022, there was much more fallowed land on the west side of the Central Valley than on the east.

Winter flooding times: While most fields are flooded from November through January, this can vary. Many farmers are involved with various bird programs that encourage farmers to flood earlier or keep their fields flooded later. Some fish food programs encourage farmers to drain their fields during the typical flooding period.

Winter straw management: How fields are managed during the winter has a large impact on habitat quality. Perhaps the biggest change in the rice industry over the past three decades was the Connelly-Areias-Chandler Rice Straw Burning Reduction Act of 1991.

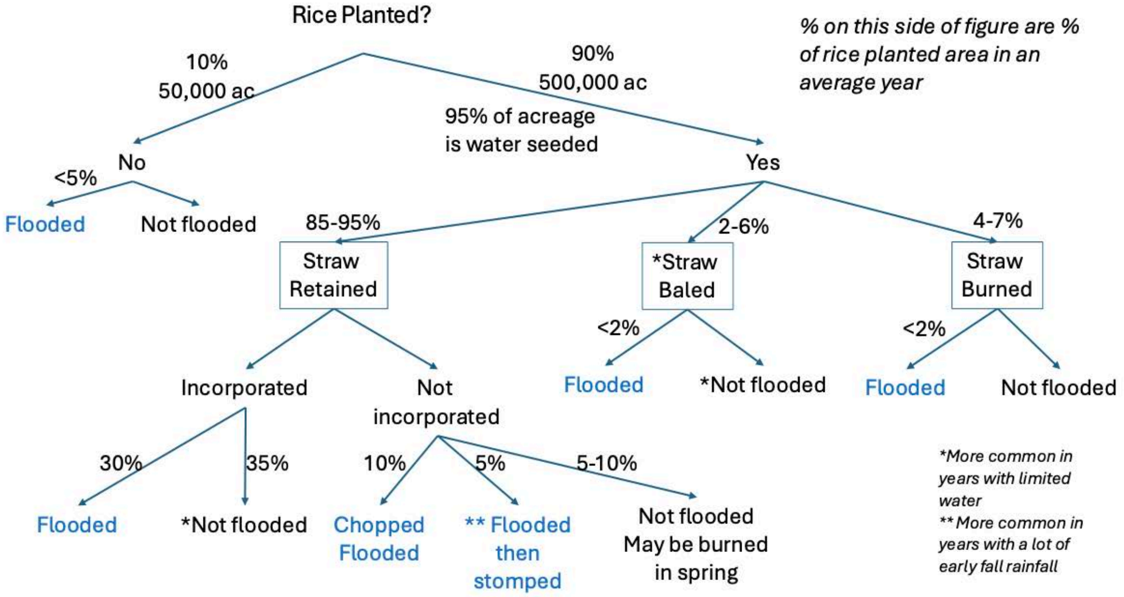

Figure 3.3: Rice straw management in an average year where water is not limiting for winter flooding. The term "Flooded" refers to intentional flooding. These estimates are based on Matthews (2019) and expert knowledge.

This phased down the practice of rice straw burning which had been the common practice of getting rid of rice straw until then. Now, most farmers incorporate their rice straw and either flood the field or leave it dry and let precipitation decompose rice straw (Fig. 3.3; Appendix A.1 Fig. 3.2). If straw is well incorporated into the soil, it is not necessary to flood the field for straw decomposition (good winter rains suffice). The cost and availability of water varies depending on the irrigation district and year. This likely affects decisions to flood fields in winter. Intentionally flooding a rice field is practiced on roughly 50% of rice fields, but this can be highly variable temporally and spatially depending on cost and availability of irrigation water. While most growers flood the fields where straw has been incorporated, fields are also flooded with the straw being chopped and left on surface. As mentioned, fields can also be flooded that were fallowed in the previous year (no straw on surface). Another variation on straw management is stomping. This practice involves growers flooding the field first and then "incorporating" straw with a stomper or cage roller. While some farmers do this routinely, others only flood and then stomp in years with a lot of early fall rain where it is not possible to use a disc or plow.

Two other methods of managing winter straw are straw burning and removal (baling). Burning is still allowed with permits but is very limited. While 25% burning is technically permitted, less than 10% of the acreage is burned. Burning requires a permit and that the straw be dry. Thus, fields are burned most commonly in the Fall before the heavy rains set in (but also in the spring). Straw baling is most common in drought periods when the cost of other straw/hay (alfalfa, wheat, etc.) is high. The Hwy 5 corridor in Colusa County is where rice baling is most common. However, in dry years, baling can be prevalent throughout the valley. Fields where the straw has been baled are sometimes flooded over the winter.

Use of ground water for irrigation: Most rice fields are irrigated with surface irrigation water provided through irrigation districts. During and following the drought in 2013 to 2015, many growers put in wells to provide more flexibility in managing their rice fields and other crops they may be growing.

Dry-seeding: Dry-seeding is planting rice into a dry soil like wheat or corn. The field is flushed with water initially to geminate seed and then the field is left in a wet unflooded state for about one month, after which the field is permanently flooded. While this only occurs on about 5% of acreage currently, there is increasing interest in the practice as a water saving practice and as a way to alternate herbicides to better control weeds. Australia used to be almost all water seeded but is now almost all dry seeded due to water limitations.

Rotation with other crops: Most rice is grown as continuous rice in California due to the very heavy clay soils that do not support other crops well. Large areas of Colusa, Glenn and Butte counties are in continuous rice. In the southern part of the Sacramento Valley, rice is more frequently rotated with other upland crops. Residue management of these upland crops does not involve winter flooding. These rotations vary a lot in terms of the frequency of rice in the rotation. A year of rice can be every 2-3 years or up to every 5-8 years.

3.4 Risk of conversion to other crops

We evaluated the potential of land-use change to California rice landscapes. Two major forms of potential change are shifts (1) to other upland crops or (2) to perennial crops (orchards). This evaluation involved surveys to understand grower's perceptions and motivations to rotate rice with other crops (Rosenberg et al., 2022), as well as the use of geospatial data to quantify land use change (Salvato et al., 2024, submitted). The details are covered in the aforementioned publications. Below are a summary of the methods and key findings.

The farmer survey of Rosenberg et al. (2022) was conducted in 2020. We interviewed 42 rice growers to (1) assess the perceived benefits and challenges of crop rotation in the context of California rice systems and (2) identify the factors influencing decision-making and barriers to rotation. For the quantitative geospatial analysis, we analyzed the period from 2008 to 2021. Annual crop data used the USDA Crop Land Data Layer (CDL). These data were augmented with data from LandIQ which provided increased accuracy on field boundaries. Data from these maps allowed us to analyze changes in land use over this period. In particular, we were interested in understanding when and where farmers were rotating rice with other field crops and if this was changing. We also analyzed when and where ricelands were being converted to orchard systems. To understand some of the drivers causing these changes, we examined soil data across the regions. Spatial soil information was obtained from the Soil Survey Geographic Database (SSURGO) developed by NRCS (NRCS Soils, 2022). We also analyzed land use changes in relation drought and crop prices.

Key findings in relation to potential shifts to more upland crop production included:

- The survey (Rosenburg et al., 2022) found that, while farmers liked the idea of rotating rice with other crops, there were several problems/challenges associated with the practice. Specifically, soil conditions were an important limitation, but other economic, social, and cultural barriers also strongly influence the potential for the diversification of rice systems (Appendix A.1 Fig. 3.3). Compared to other field crops, rice is economical. Several farmers also remarked that they valued the wildlife habitat contribution from ricelands.
- As a result, the primary rice growing counties of Colusa, Glenn and Butte had very little crop rotation (Fig. 3.4).
- Rotation of rice with other crops primarily occurred in the southern portion of the Sacramento Valley and mostly in Sutter and Yolo counties.

- During the study period, crop rotations overall decreased in rice systems. It roughly halved during the study period (Appendix A.1 Fig. 3.4). The likely reason for this is the use of subsurface irrigation in other field crops which make it hard to fit in with rice.
- Rotations occurred on certain types of soil (driven by soil pH, EC and hydraulic conductivity). Factoring in these soil variables, about 11% of the continuous rice acreage could potentially support rotations with other crops. So, these data support those of Rosenburg et al. (2022), indicating that soil is a major limitation.

Secondly, we assessed the likelihood of rice being converted to perennial crop systems (*i.e.,* orchards, such as almonds and walnut). This represents a more permanent and long-term change. These data are, as of yet, unpublished but have been submitted.

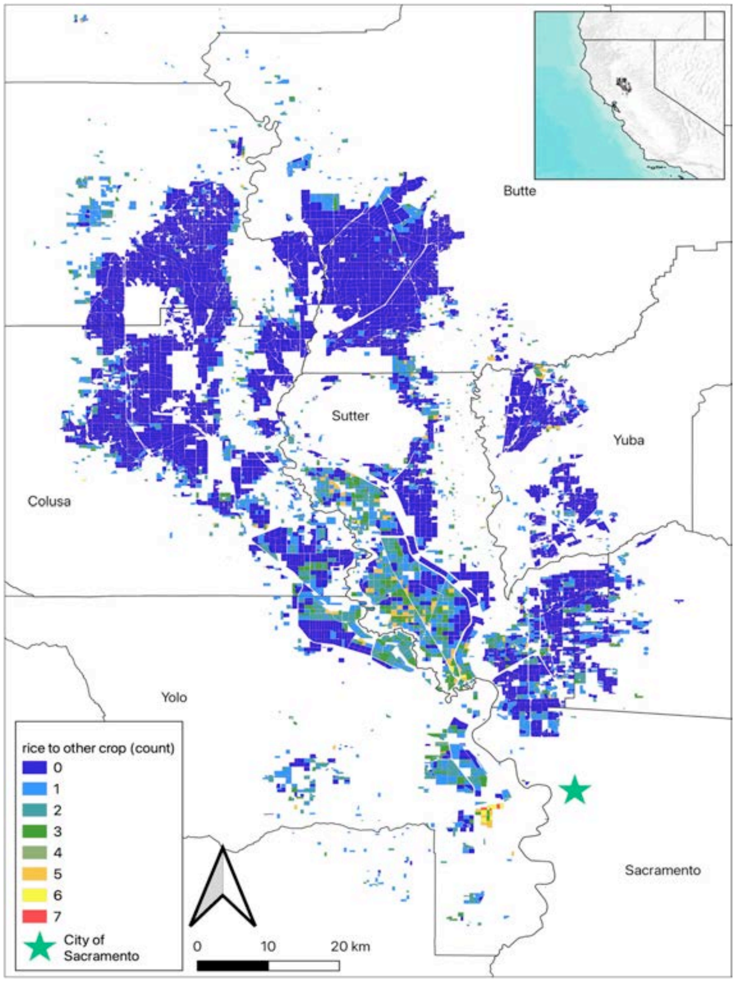

Figure 3.4: Rice rotation frequency map showing the number of times a field changed from rice to alternate crop (i.e. annual crop, alfalfa, forage, pasture, etc.) in the 15- year data set. Fields converted to perennial trees were excluded. A count of 0 implies continuous rice, while a count of 6 or 7 implies the field is rotated annually.

In brief, we found:

- During the study period (2008 to 2021), almonds and walnuts were the main orchard crops that replaced rice (Fig. 3.5). In total, about 25,000-30,000 acres of riceland was converted to these two orchard crops.
- Despite these crops being larger users of water and requiring a steady annual supply of water, conversion to almonds and walnuts began during the drought period (2013-2015). It was largely driven by good prices for both almond and walnuts at that time (Appendix A.1 Fig. 3.5).
- The clay content in the soil was the most important variable determining if trees could be grown (Fig. 3.6).
- Most replacement of rice with orchard crops occurred on the periphery of the rice area (not in the interior), although walnuts did replace rice along some of the areas adjacent to the rivers (Fig. 3.6).

In summary, under current economic conditions, it is hard to imagine the baseline rice acreage falling below 450,000 acres. In addition to economics, soils do not support such a conversion. Furthermore, rice acreage in Colusa, Glenn and Butte counties is the most consistently in

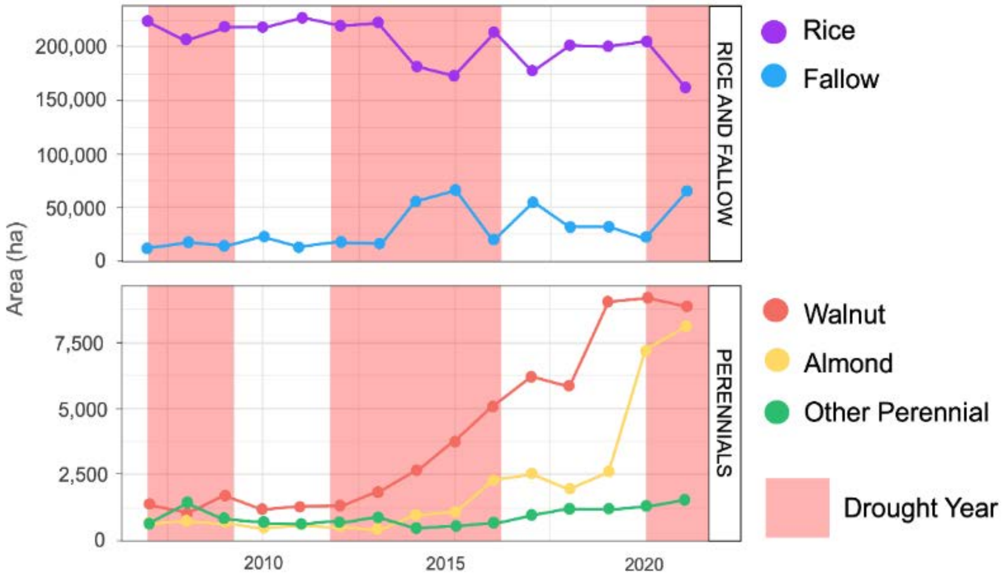

Figure 3.5: Time series area (hectares) for rice and fallow (top) and walnut, almond, and other perennial crops (bottom). Red shading indicates drought years.

continuous rice. While perennial crops have increased, it is on the periphery of these large basins and along the rivers. That said, while the base-acres of rice may be high, there are years with a lot of fallowing, causing the planted acres to dip as low as 256,000 acres (as in 2022).

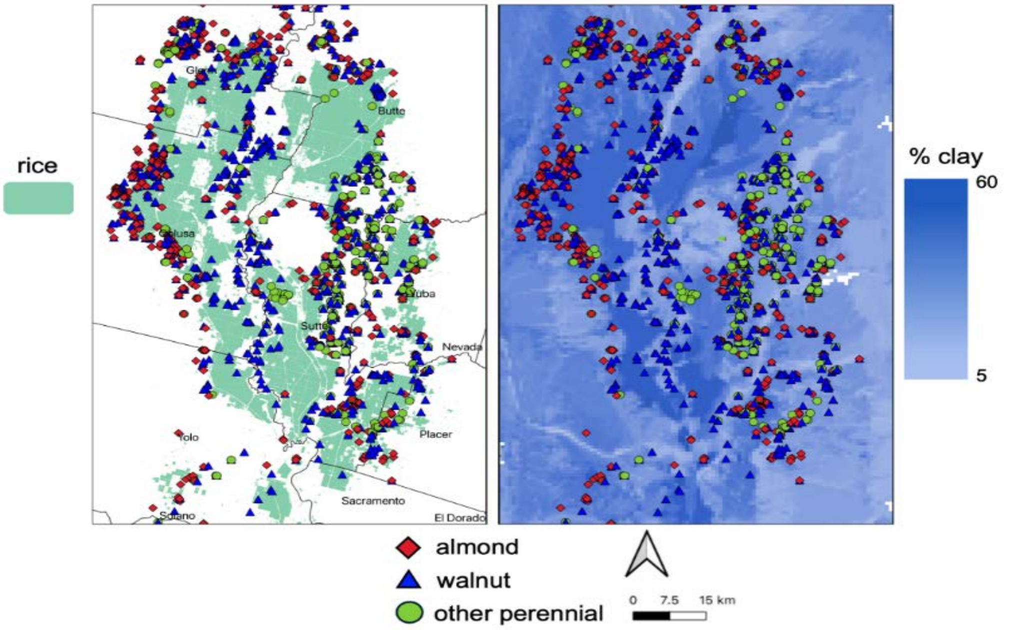

Figure 3.6 Map showing the location of new almond, walnut, and other perennial plantings in the rice growing area (left) and the background clay content (%) in the region (right).

3.5 References

Matthews, L. 2019. Changing Post-harvest Practices, Impacts on Waste Grain Availability, and Grower's Perspectives: A study of rice and corn fields for wintering waterfowl in the Central Valley. MSc thesis, University of California, Davis.

Rosenberg, S., A. Crump, W. Brim-DeForest, B. Linquist, L. Espino, K. Al-Khatib, M.M. Leinfelder-Miles, C.M. Pittelkow. 2022 Assessing crop rotation feasibility for rice systems in California: Baseline assessment of barriers and opportunities. Frontiers in Agronomy. doi.org/10.3389/fagro.2022.806572

Salvato, L., Pittelkow, C., O'Geen, T. and Linquist, B.A. (2024) A geospatial assessment of soil properties to identify the potential for crop rotation in rice systems. Agriculture, Ecosystems and Environment doi.org/10.1016/j.agee.2023.108753.

Salvato, L., Pittelkow, C., and Linquist, B.A. (Submitted) Evaluating agricultural land use change in relation to environmental, biophysical, and economic drivers. Agricultural Systems

4. Mapping Methods and Scenario Generation

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Highlights

- To evaluate the importance of rice acreage for multiple species of wildlife in the context of current agronomic practices, we needed a well-defined and agreed-upon delineation of habitat types and locations in the Central Valley. Our mapping process involved a comprehensive GIS-based approach, integrating diverse datasets to quantify habitat characteristics, spatial relationships, and temporal dynamics across the Central Valley.
- We consolidated and updated existing map information from a variety of sources and partners to provide a baseline map. We used data from 2020 to 2024 to map the acreage and distribution of rice in production, flooded rice, other crops, and managed wetlands to capture the variability in habitat availability across years.
- To provide a range of realistic observed scenarios representing different habitat conditions, we developed five distinct habitat scenarios using data from the fall and winter of four recent years representing a range of conditions, from favorable years with extensive rice planting (>500,000 rice acres in 2020/21 and 2023/24) to challenging years with reduced planting due to drought (~250,000 rice acres in 2022/23,).
- Peak wet rice acreage in favorable years reached approximately 285,000 acres, while the challenging 2022/23NR scenario saw a sharp decline, with peak wet acreage dropping to 130,000 acres. Managed wetland flooding was a more stable component of the landscape, ranging between 90,000 and 100,000 wet acres annually, except in years with substantial unplanned rainfall (e.g., 2023).
- This mapping effort provides the foundation for evaluating habitat needs across taxa, offering a unified framework for scenario generation and spatial analysis.

4.1. Background and context

To understand the importance of rice for each wildlife taxa, we needed to harmonize a single baseline mapping framework that included flooded and dry rice, other crops, managed wetlands, and other habitat components that could influence the abundance and distribution of various wildlife species. Several new habitat mapping programs and approaches have become available (e.g. WET, https://iwjv.org/solution-based-science/wet/; Water Tracker, https://data.pointblue.org/apps/autowater/), but these tools have been used primarily to generate maps that vary according to the specific taxa or conservation issues under consideration (Reiter et al. 2015, Matchett and Fleskes 2017, 2018, Reiter et al. 2018a, Matchett 2021, Donnelly et al. 2021, 2022, 2022, Conlisk et al. 2022, Bunting et al. 2022). We lacked a single integrated map that provided well-defined and agreed-upon delineation of habitat types and locations which could enable consideration of alterative scenarios of habitat availability.

Our mapping process involved a comprehensive GIS-based approach, integrating diverse datasets to quantify habitat characteristics, spatial relationships, and temporal dynamics across the Central Valley. By doing so, we created a robust framework for generating habitat scenarios and supporting analyses across taxa.

4.2 Study area

The study area for this analysis encompassed the rice-growing region of California's Central Valley. This region spans approximately 20,000 square miles, extending from Red Bluff in the north to Stockton in the south, and includes six major basins: Colusa, Butte, American, Sutter, Yolo, and Delta. These basins correspond to the planning regions identified in the Central Valley Joint Venture (CVJV) 2020 Implementation Plan, which prioritizes habitat conservation for waterfowl and other species.

Historically, extensive natural wetlands in the Central Valley provided vital habitat for wildlife. However, agricultural and urban development have significantly altered the landscape. Today, flooded rice fields, managed wetlands, and remnant natural habitats serve as surrogates for the wetlands that have been lost. The region's landscape is a mosaic of agricultural fields, managed wetlands, and urban areas, with habitat availability and quality varying substantially based on annual environmental conditions and management practices. Figure 4.1 shows the study area, highlighting the diversity of landcover types within the region.

We consolidated and updated existing map information from a variety of sources and partners, including USGS, USDA, Point Blue, Ducks Unlimited, and USFWS (Petrik et al. 2013, Matchett, et al. 2015, Reiter et al. 2015, 2018a, 2018b, Matchett and Fleskes 2017, 2018, Matchett 2021, Donnelly et al. 2021, 2022, 2022, Conlisk et al. 2022), to provide a baseline map for this study. We used data from 2020 to 2024 to map the acreage and distribution of rice in production, flooded rice, other crops, and managed wetlands to capture the variability in habitat availability across years.

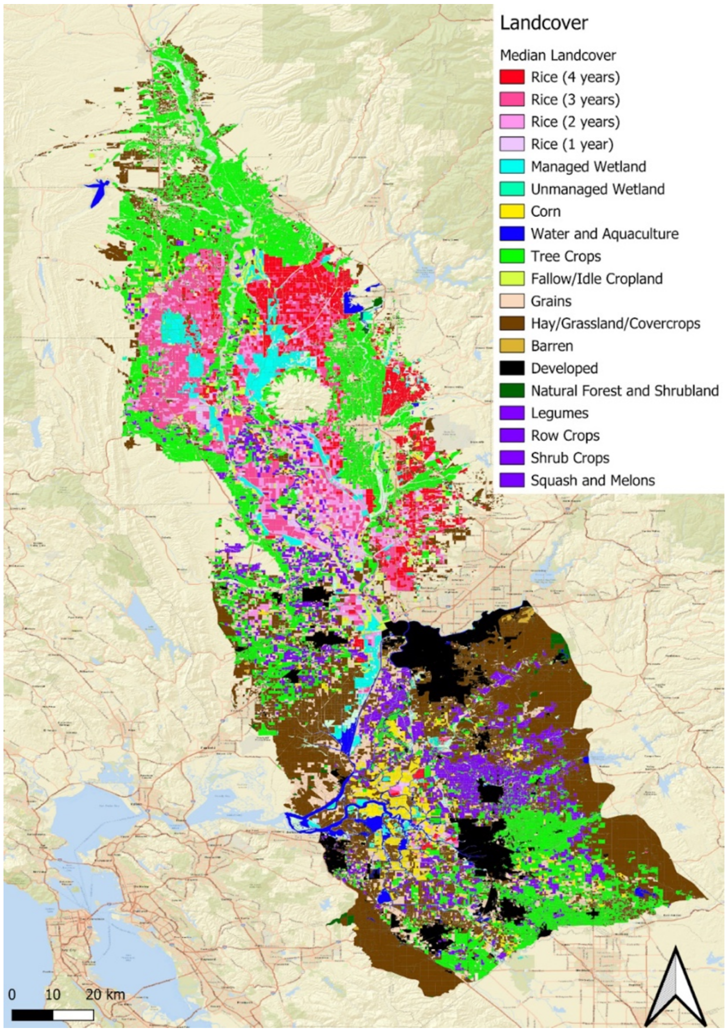

Figure 4.1: Median Landcover Map of the Central Valley Study Area. The map illustrates the predominant landcover types in the Central Valley of California over a four-year period, highlighting key habitat types including rice fields, managed and unmanaged wetlands, and other agricultural and natural landcovers. Rice fields are categorized by the frequency of cultivation 1–4 years, shown in varying shades of red and pink. Corn agriculture is in yellow. Managed wetlands are represented in cyan, while unmanaged wetlands are in teal. The map also includes other habitat types, such as tree crops, grains, fallow/idle cropland, and aquaculture, as well as non-agricultural areas like developed lands and natural forests. This spatial distribution underscores the complex land-use mosaic that supports diverse wildlife, including waterfowl and other taxa, within the study area.

4.3 Habitat scenarios

To provide a range of realistic observed scenarios representing different habitat conditions, we developed five distinct habitat scenarios using data from the fall and winter of four recent years (i.e., 2020/2021 to 2023/2024), along with one alternative hypothetical scenario for

2022/2023 (termed 22/23NR). These scenarios represent a range of conditions, from favorable years with extensive rice planting (as in 2020/21 and 2023/24 with >500,000 rice acres) to challenging years with reduced planting due to drought (as in 2022/23, ~250,000 rice acres). The 22/23NR ‘no rain scenario; was constructed to exclude the effects of heavy late winter rainfall observed in 2023, modeling a consistent drought condition for comparative analysis.

Figure 4.2 illustrates the total crop acreage across these years, highlighting the variation in rice, corn, wheat and barley. Table 4.1 provides additional detail, summarizing the maximum monthly wet acreage for rice, corn, and wetlands within each scenario. Peak wet rice acreage in favorable years reached approximately 285,000 acres, while the challenging 22/23NR scenario saw a sharp decline, with peak wet acreage dropping to just 130,000 acres. Managed wetland flooding, a more stable component of the landscape, ranged between 90,000 and 100,000 wet acres annually, except in years with substantial unplanned rainfall (e.g., 2023).

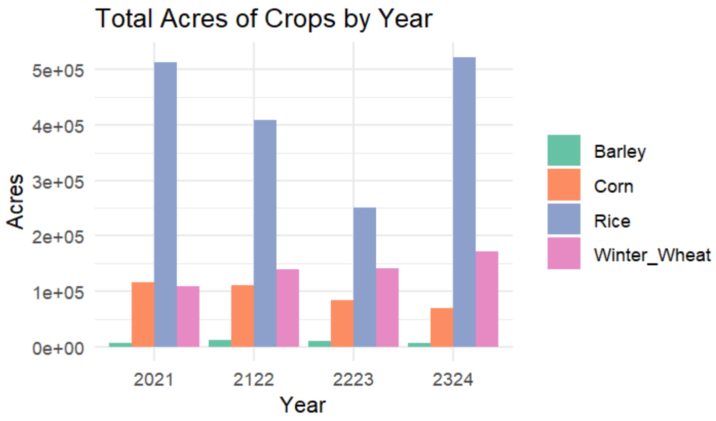

Figure 4.2. Total Acres of crops by Year in the Central Valley (approximately Chico to Modesto). This bar chart shows the annual acreage of four crop types—rice, corn, winter wheat, and barley—from 2021 to 2024. Rice consistently accounts for the largest proportion of agricultural land use, with acreage fluctuating across years, peaking in 2020/21 and 2023/24, and declining sharply during the drought year of 2022/23. Corn and winter wheat exhibit relatively stable trends, while barley contributes minimally to the overall crop acreage. These variations highlight the dynamic nature of agricultural practices in the region, influenced by environmental and economic factors, and the critical role of rice in supporting wildlife habitat, especially during winter.

Table 4.1. Maximum Total and Wet Acres of Rice, Corn, and Wetlands by Year. This table summarizes the total acreage and the maximum wet acreage of rice, corn, managed wetlands, and all wetlands (including wetlands flooded passively) across five years, including the modeled 2022/23NR scenario. We differentiate between managed and passive wetland acres because these habitats have different food values for waterfowl. Wet rice acreage shows significant variation, with 2020/21 and 2023/24 reaching the highest levels, while drought-impacted years like 2022/23 exhibit the lowest. Managed wetlands provide a stable contribution to wetland habitat across all years.

Year	Total Rice	Max. Wet Rice	Corn	Max. Wet Corn	Managed Wetland	Max. Wet Wetland	All Wetland	Max. All Wet
20/21	517,999	270,384	116,548	17,706	112,798	95,463	132,660	106,249
21/22	411,927	228,205	109,856	13,468	112,789	99,660	133,646	112,392
22/23	253,526	219,631	84,434	19,214	112,810	108,613	134,240	126,962
22/23NR	253,526	131,883	84,434	7,120	112,810	90,018	134,240	101,105
23/24	525,775	285,835	70,293	9,688	112,740	99,616	134,154	112,734

4.4 Mapping and Data Integration

Habitat Classification:

- Agricultural and Wetland Classification: Agricultural landcover was classified using USDA Crop Data Layers CDL for 2020–2024. (https://www.nass.usda.gov/Research_and_Science/Cropland/SARS1a.php). Wetlands were further classified using high-resolution maps from Audubon, Ducks Unlimited, Point Blue, and

USGS (Matchett, et al. 2015, Reiter et al. 2015, 2018a, 2018b, Matchett and Fleskes 2017, 2018, Matchett 2021, Donnelly et al. 2021, 2022, 2022, Conlisk et al. 2022). These layers provided detailed spatial representations of managed and passive wetlands, rice fields, and other habitat types.

- Enhanced Accuracy: Multiple data sources were cross-referenced to enhance classification accuracy, with manual adjustments made for areas where automated methods were insufficient. Wetland classifications incorporated management status and habitat condition data to better reflect ecological significance.

Water Coverage Analysis:

- Satellite Imagery: Seasonal flooding patterns were analyzed using Patrick Donnelly's Wetland Evaluation Tool WET from USFWS (https://iwjv.org/solution-based-science/wet/;), which relies on satellite imagery to monitor water coverage in both agricultural and natural wetland habitats. These data allowed for a detailed monthly accounting of wet acreage for each scenario.
- Temporal Dynamics: Monthly wet acreages were calculated for each habitat type, revealing the timing and extent of seasonal flooding. Figure 4.3 illustrates these dynamics, showing the wet rice and managed wetland acreage across the five scenarios.

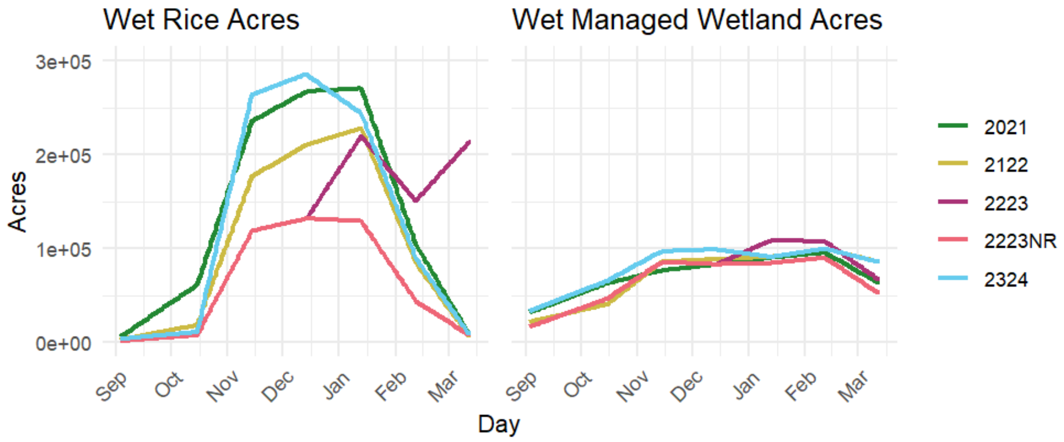

Figure 4.3. Seasonal Trends in Wet Acres for Rice and Managed Wetlands by Year. The left panel illustrates the seasonal fluctuation in wet rice acres across five years, with peaks typically occurring in January. Wet rice acreage varies significantly, with the highest levels observed in 2020/21 and 2023/24 and the lowest in the drought-affected year of 2022/23. The 2022/23NR scenario, which excludes winter rainfall, further emphasizes the impact of drought on wet rice availability. The right panel displays wet managed wetland acres, showing more stability across years compared to rice. While managed wetlands provide a relatively consistent source of habitat, they lack the large seasonal peaks seen in rice. Together, these trends highlight the dynamic contribution of wet rice and the steady role of managed wetlands in supporting wildlife habitat during the critical winter months.

Spatial Integration:

- Parcel Mapping: The landscape was divided into parceled polygons, incorporating data from LandIQ (https://www.landiq.com) and other sources. These polygons formed the basis for spatial analyses, enabling precise calculations of habitat overlap, flooding extent, and connectivity. The complete workflow for parcel mapping, including steps for resolving overlapping geometries and integrating wetland unit boundaries, is outlined in Appendix A.2.

- Zonal Statistics: Metrics such as wetland coverage, flooding duration, and proximity to key habitat features were calculated for each parcel. This provided a spatially explicit understanding of habitat quality and availability.

Scenario Development:

- Each scenario integrated habitat and water coverage data to represent both typical and extreme conditions. These scenarios were designed to assess the effects of annual fluctuations in rice planting and wetland flooding on habitat availability, serving as a baseline for evaluating the habitat needs of waterfowl and other taxa.

4.5 Role in the Project Framework

This mapping effort provides the foundation for evaluating habitat needs across taxa, offering a unified framework for scenario generation and spatial analysis. By integrating diverse data sources and leveraging advanced GIS tools, the framework ensures consistency across the project's interdisciplinary efforts. It allows for:

- **Comparative Analysis**: The scenarios support comparisons across taxa, helping to identify overlaps and trade-offs in habitat requirements.
- **Scenario Evaluation**: The mapping framework enables the simulation of various management and environmental scenarios, assessing their impacts on habitat availability and species outcomes.
- **Informed Decision-Making**: The insights gained from this framework can guide adaptive management strategies, helping stakeholders balance conservation goals with agricultural needs.

The comprehensive nature of this framework ensures that the project's findings are grounded in a detailed understanding of the Central Valley's dynamic landscape, providing a robust basis for future analyses and conservation planning.

4.6 References

Bunting, D. P., M. A. Boggie, D. P. Collins, P. P. Thorpe, and J. P. Donnelly. 2022. Linking ecological processes and animal movements to inform timing of long-term surveys of a migratory game bird. Ecosphere 13:e4298.

Conlisk, E. E., G. H. Golet, M. D. Reynolds, B. A. Barbaree, K. A. Sesser, K. B. Byrd, S. Veloz, and M. E. Reiter. 2022. Both real-time and long-term environmental data perform well in predicting shorebird distributions in managed habitat. Ecological Applications 32:e2510.

Donnelly, J. P., S. L. King, J. Knetter, J. H. Gammonley, V. J. Dreitz, B. A. Grisham, M. C. Nowak, and D. P. Collins. 2021. Migration efficiency sustains connectivity across agroecological networks supporting sandhill crane migration. Ecosphere 12:e03543.

Donnelly, J. P., J. N. Moore, M. L. Casazza, and S. P. Coons. 2022. Functional Wetland Loss Drives Emerging Risks to Waterbird Migration Networks. Frontiers in Ecology and Evolution 10:844278.

Matchett, E. L. 2021. Using High Resolution Satellite and Telemetry Data to Track Flooded Habitats, Their Use by Waterfowl, and Evaluate Effects of Drought on Waterfowl and Shorebird Bioenergetics in California. Open-File Report.

Matchett, E. L., and J. P. Fleskes. 2017. Projected Impacts of Climate, Urbanization, Water Management, and Wetland Restoration on Waterbird Habitat in California's Central Valley. PLOS ONE 12:e0169780.

Matchett, E. L., and J. P. Fleskes. 2018. Waterbird Habitat in California's Central Valley Basins Under Climate, Urbanization, and Water Management Scenarios. Journal of Fish and Wildlife Management 9:75–94.

Matchett, E. L., Joseph P. Fleskes, Charles A. Young, and David R. Purkey. 2015. A Framework for Modeling Anthropogenic Impacts on Waterbird Habitats—Addressing Future Uncertainty in Conservation Planning. Page 40. Open-File Report, U.S. Geological Survey Open-File Report 2015-1017.

Petrik, K. L., D. Fehringer, and A. Weverko. 2013. Mapping Seasonal Managed and Semi-permanent Wetlands in the Central Valley of California. Final Report, Ducks Unlimited, Inc. - Western Regional Office, Rancho Cordova, CA.

Reiter, M. E., N. K. Elliott, D. Jongsomjit, G. H. Golet, and M. D. Reynolds. 2018a. Impact of extreme drought and incentive programs on flooded agriculture and wetlands in California's Central Valley. PeerJ 6:e5147.

Reiter, M. E., N. K. Elliott, D. Jongsomjit, G. H. Golet, and M. D. Reynolds. 2018b. Impact of extreme drought and incentive programs on flooded agriculture and wetlands in California's Central Valley. PeerJ 6:e5147.

Reiter, M. E., N. Elliott, S. Veloz, D. Jongsomjit, C. M. Hickey, M. Merrifield, and M. D. Reynolds. 2015. Spatio-Temporal Patterns of Open Surface Water in the Central Valley of California 2000-2011: Drought, Land Cover, and Waterbirds. JAWRA Journal of the American Water Resources Association 51:1722–1738.

5. Evaluation of Individual Taxonomic Groups

5.1 A conservation footprint in California rice for Giant Gartersnake

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Highlights

- The Giant Gartersnake Endangered Species Recovery Plan prescribes 83,634 acres of cultivated rice paired with wetlands across recovery units, an amount that is surpassed even in recent drought years. The amount of ricelands *per se* is thus less limiting than the timing, location, and management of it to maximize its value to GGS.
- Key areas for GGS recovery include rice fields that are consistently flooded and close to existing wetlands. Drought-affected basins, such as those south of the Sutter Buttes, show potential for integration into key habitat with improved water availability.
- Synchronizing water delivery to better match GGS spring emergence is essential. Early flooding of canals or adjacent areas may provide viable solutions to the need for early-season habitat and gartersnake prey.
- Studies are needed on topics like rice crop consistency during droughts, water availability timing, size of minimum viable populations, the role of upland and rice field management practices, and genetic diversity to refine GGS conservation strategies.
- Improving the spatial arrangement of rice fields relative to wetlands, enhancing water management, and addressing knowledge gaps can further align agricultural practices with GGS recovery goals, balancing conservation with productivity.

5.1.1 Background and context

The Giant Gartersnake (*Thamnophis gigas*; hereafter 'GGS') is a semi-aquatic species found only in California's Central Valley. It was historically found in marshes and wetlands, but now also persists in rice fields and irrigation canals where it feeds on fish and amphibians (Halstead et al. 2010, Halstead et al. 2019; Ersan et al. 2020). It is found within 20 m of aquatic habitat year-round— using it for feeding and mating when active from April–October. That said, it relies on shores, banks, and uplands with emergent vegetation to bask and rest as well as to spend its winter months buried underground (Halstead et al. 2015a; Halstead et al. 2021). It gives birth to young in July–September and has high variation in survival, which increases the need for stable and suitable habitat to support populations (Rose et al. 2018a).

Due to the loss of historical wetlands in California's Central Valley, rice fields have become critical surrogate habitats for GGS (Halstead et al. 2014; Halstead et al. 2019). These managed, flooded fields provide essential habitat that mimics the historical habitat where GGS feed and live (Halstead et al. 2014; Halstead et al. 2016). In summer, GGS use rice fields and associated canals because they offer both aquatic prey and emergent vegetation for basking and shelter (Halstead et al. 2016). The actual fields themselves, however, may not be ideal year-round. GGS rely on upland habitats, adjacent wetlands, and other aquatic features such as irrigation canals to meet needs that can vary seasonally (Valcarcel 2011; Halstead et al. 2015a,b,c).

Rice agriculture presents several opportunities or challenges for GGS. These include:

1. **Loss of Rice Habitat**: Reduction in the amount of rice agriculture challenges GGS. Changes in land use, water availability, and economic factors have led to a decline in rice fields or idling of fields in some years, reducing habitat for GGS when active, which in turn decreases survival and population connectivity (USFWS 2017; Halstead et al. 2019).
2. **Rice Management**: Management of rice fields can shape GGS conservation, including
    - **Variation in Timing**: The timing of flood-up and water availability in rice fields may not align with the needs of GGS. GGS emerge from brumation in early April, for example, but many fields are flooded later. This mismatch likely reduces GGS survival at a critical time when snakes need aquatic habitat and food but find none in dry canals and fields (Halstead et al. 2015b; Rose et al. 2018; Halstead et al. 2019).
    - **Water Characteristics**: If fields or canals are too deep or too shallow, they may not support prey populations for GGS (Halstead et al. 2010; Halstead et al. 2019).
    - **Management of Uplands**: Maintenance of irrigation canals and management of vegetation and riprap along canals can affect GGS year-round when they are out of the water, including when they are underground during winter brumation in shallow burrows (Halstead et al. 2015a; Reyes et al. 2017; Halstead et al. 2021).
3. **Spatial Arrangement of Rice Fields**: The proximity of rice fields to habitats like wetlands is critical for GGS movement and dispersal. GGS rely on wetland–rice mosaics to support their habitat needs year-round. If rice fields are isolated from wetlands, other types of land use can pose barriers to movement. Inadequate connectivity between habitats can lead to genetic and demographic isolation, limiting population growth (Paquin et al. 2006; Valcarcel 2011; Halstead et al. 2014; Wood et al. 2015).

5.1.2 Methods

We reviewed the Giant Gartersnake recovery plan (USFWS 2017) and its prescribed targets for the amounts of wetlands or ricelands needed to benefit the species in order to tabulate acreage targets needed. We also reviewed the broader literature on GGS to identify unknowns for which answers may benefit GGS management as well as identify any key recommendations that if implemented may benefit GGS populations. We used ArcGIS Pro (ArcGIS Pro version 3.3.0, Esri 2024) to produce maps and for geospatial analysis. Our process followed three steps: data, collection, spatial analysis, and interpretation.

Data Collection: We obtained GGS occurrence records from the California Natural Diversity Database (queried August 2, 2024). We mapped these occurrences for three time periods: historical occurrences (<1980), mid-range occurrences (1980–2000), and recent occurrences (>2000).

Land use data were compiled into a GIS layer on a parcel-by-parcel basis for the Sacramento Valley for water years October 1, 2022 to September 30, 2024 (see section 4 above). Rice parcels were classed by how many years they were flooded for rice cultivation out of the four water years. We used buffer distances of 0.8 km (0.5 mi) around GGS occurrences based on the distance a GGS can travel in one day (Hansen and Brode 1993; USFWS 2017). Additionally, we used a buffer distance of 55 meters (180 feet) around riceland parcels to account for adjacent canals and berms frequently used by GGS. The USFWS Recovery Plan prescribes the preservation of pairs of 240-ha (539 ac) wetland blocks or at least one wetland and one 639-ha (1578 ac) active riceland within 8 km (5 mi) of one another. The number of prescribed block pairs differs among nine recovery units described for GGS (Figure 5.1.1; Table 5.1.1) and reflects the size of each recovery unit and its available suitable habitat (USFWS 2017). The acreage requirement for the wetland blocks was based on the size of habitat at Badger Creek wetland, where a self-sustaining population of GGS has been studied (Wylie et al. 2010). The acreage requirement for the riceland blocks was based on the lower density of snakes found in rice fields from the same study (Wylie et al. 2010). Critically, it is unclear whether these habitat sizes are sufficient to support a minimum viable population, especially given orders of magnitude difference in snake densities among rice fields (Halstead et al. unpubl. data).

Spatial Analysis: Using ArcGIS Pro's spatial analysis tools, we overlaid GGS occurrences with the land use layer to visualize the distribution of historical, mid-range, and recent occurrences (Figure 5.1.2). We used spatial join and intersection analyses to examine the habitat types within the 0.5-mile buffer of each GGS occurrence. We then calculated the area of current rice fields and wetlands to determine how well current availability or cultivation matches the habitat block-pair recommendations from the GGS Recovery Plan. We overlaid recent GGS occurrences (since the year 2000) over these habitat areas to determine areas of high priority, intermediate priority, and low priority for GGS management actions.

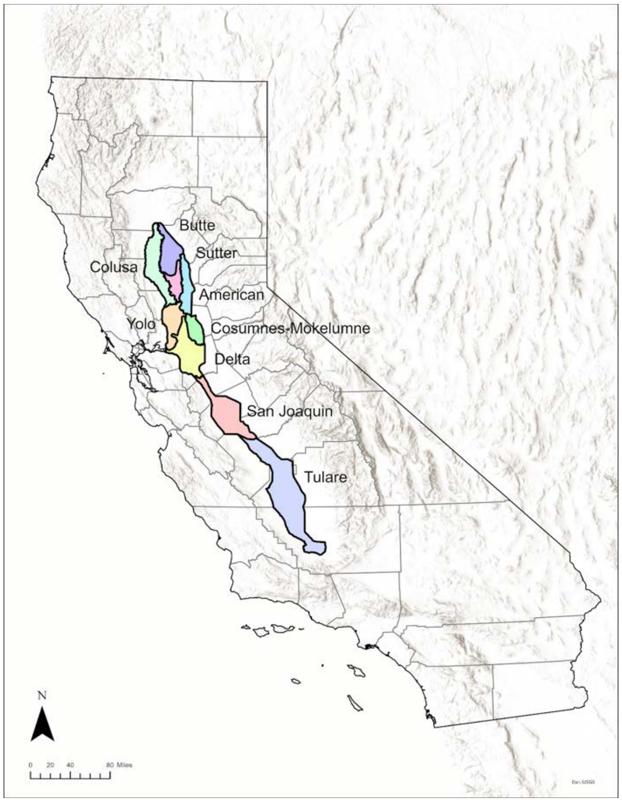

Figure 5.1.1. Map showing the nine recovery units defined for the Giant Gartersnake in the 2017 USFWS Recovery Plan.

Table 5.1.1: Recommended rice acreage for Giant Gartersnakes in each recovery unit, as outlined in the 2017 USFWS Recovery Plan. The table includes the number of block pairs prescribed for each recovery unit, the size of one riceland block in a given block-pair (1,578 acres), and the total target rice acreage required to support GGS populations.

Recovery Unit	Number of Block Pairs	Size of One Riceland Block (acres)	Target Rice acreage (acres)
Butte	6	1,578	9,468
Colusa	6	1,578	9,468
Sutter	4	1,578	6,312
American	8	1,578	12,624
Yolo	5	1,578	7,890
Cosumnes-Mokelumne	2	1,578	3,156
Delta	10	1,578	15,780
San Joaquin	10	1,578	15,780
Tulare	2	1,578	3,156
Total			**83,634**

Areas of high priority were defined as rice parcels that met the habitat recommendation of the Recovery Plan (639-ha, 1578 ac, or larger), were within 5 miles of wetland parcels of recommended size (240-ha, 539 ac, or larger), and had GGS occurrences since the year 2000. Areas of intermediate priority were defined as rice parcels that met the habitat recommendation of the Recovery Plan (639-ha, 1578 ac, or larger) and were within 5 miles of wetland parcels of recommended size (240-ha, 539 ac, or larger), but did not have GGS occurrences since the year 2000. Areas of low priority were defined as all other rice parcels.

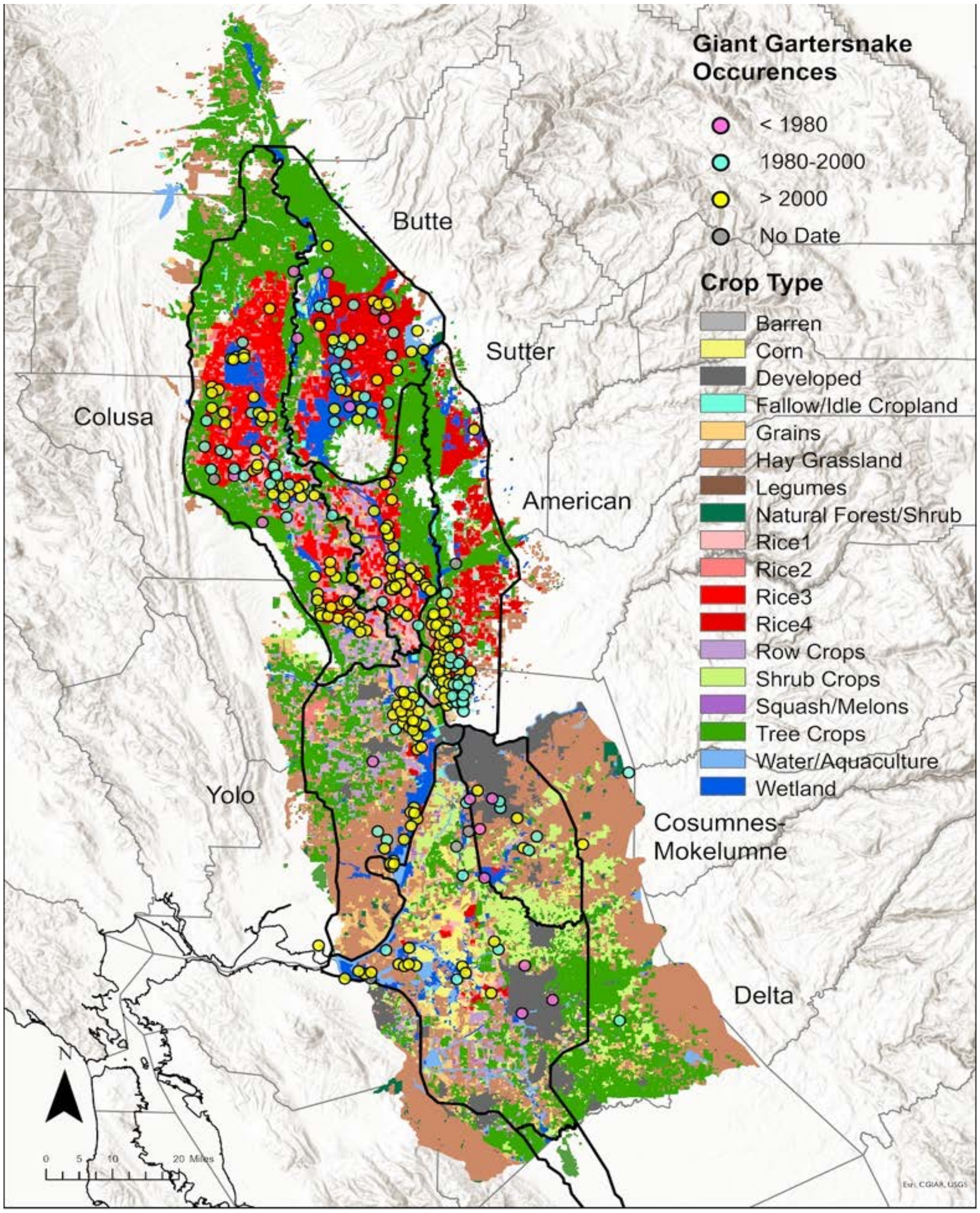

Figure 5.1.2. Map showing the nine recovery units defined for the Giant Gartersnake in the 2017 USFWS Recovery Plan with Giant Gartersnake occurrences overlaid by year of observation. The occurrences were obtained from the California Natural Diversity Database queried August 2024 and managed by the California Department of Fish and Wildlife.

Interpretation: Maps generated from this analysis display GGS occurrences over time and show how they correspond with current land use. The maps also provide at least one means of prioritizing areas where rice cultivation and management consistent with GGS populations may best meet recovery goals.

5.1.3 Results

The spatial analysis revealed key areas of opportunity for Giant Gartersnake recovery.

Total Habitat Acreage: The GGS Recovery Plan would require 83,634 acres of cultivated (i.e., flooded) rice to meet recovery criteria if each pair of habitat blocks included one rice parcel paired with a wetland instead of two wetlands (Table 5.1.1). The total acreage of cultivated rice in the study site varied across the analysis period of 2020–2024, with a high of 546,932 acres in an average water year (2023–24 water year) and a low of 259,182 acres in the drought year (2022–23 water year). Rice fields likely suitable for GGS (based on recent occurrences, recommended acreage, and proximity to wetland habitat) comprised a fraction of the annual total rice in cultivation, with a lower bound of 158,110 acres in a drought year and an upper bound of 459,126 acres in an average water year (Table 5.1.2). Based on acreage alone, it appears that habitat availability is less a limiting factor in many recovery units than the appropriate timing and management that shape the suitability of ricelands for GGS populations.

Key Priorities for Spatial Location of Rice: The analysis identified several areas where rice fields are positioned near wetlands and could be managed for GGS (Figure 5.1.3). First, GGS occurrences clustered around rice fields that had cultivated rice more consistently each year and were closer to wetland habitat. Second, basins like Sutter, American, and Yolo, where much of the rice was idled in recent droughts (e.g., south of the Sutter Buttes) also emerged as priorities, particularly if these fields could be reintegrated into GGS habitat corridors with improved consistency of water availability/delivery. Third, the analysis indicated that many areas could achieve the recovery plan's target acreage recommendations (i.e., a 539-acre wetland paired with 1,578 acres of rice, separated by no more than 5 miles). That said, our results suggest that it is not necessarily the amount of rice acreage, but rather how that rice is managed—such as timing of water availability, proximity to wetlands, and connectivity between habitats— that will have the greatest impact on GGS conservation.

Key Priorities for Rice Management: Ultimately, the suitability of rice fields as GGS habitat relies heavily on water management practices. The analysis highlighted the following priorities:

- Water Timing: Synchronizing the flooding of rice fields or associated canals with GGS spring emergence is critical. Currently, the later start to rice field flooding each spring limits food and habitat availability for snakes as they emerge from brumation, affecting early-season survival (Halstead et al. 2015b; Rose et al. 2018b; Halstead et al. 2019). Where early rice flooding is impractical, early flooding of adjacent irrigation canals may serve as a viable alternative, but needs study. Such canals may provide early-season aquatic prey and refuge, addressing a key bottleneck in GGS survival (Reyes et al. 2017).
- Proximity to Wetlands: Rice fields closer to wetlands were more likely to have recent GGS occurrences than those farther away. More distant rice fields may be suitable, but they had few recent occurrences and appear isolated from wetlands, and thus may be limited to act as functional habitat for GGS, indicating the need for improved corridor development. We recommend caution in interpreting the distribution of GGS occurrences though because they often reflect where the species is targeted for study and are not the result of systematic, unbiased sampling for GGS across all areas

Table 5.1.2. Rice acreage classified as High Priority, Mid Priority, and Low Priority for Giant Gartersnake habitat across recovery units in the Central Valley, California, from water years October 2020–September 2024. High Priority parcels are at least 1,578 acres in size, within 5 miles of sufficiently large wetland parcels, and have recent occurrences since 2000; Mid Priority parcels are sufficiently large and close enough to wetland parcels but lack recent occurrences; Low Priority parcels are all other ricelands that fall outside these classifications. Values reflect changes in acres of rice cultivation across four water years October 2020–September 2024. We were not able to estimate values for the San Joaquin and Tulare recovery units given insufficient data on land cover types by parcel in the southern Central Valley, CA.

	2020-2021			**2021-2022**			**2022-2023**			**2023-2024**		
Recovery Unit	**High Priority**	**Mid Priority**	**Low Priority**	**High Priority**	**Mid Priority**	**Low Priority**	**High Priority**	**Mid Priority**	**Low Priority**	**High Priority**	**Mid Priority**	**Low Priority**
Butte	138,481	0	5,405	98,179	0	12,861	99,737	0	10,253	132,733	0	5,265
Colusa	178,446	20	21,835	12,225	110,030	36,321	3,648	0	22,938	190,654	0	20,181
Sutter	52,516	0	19,960	21,748	0	26,902	8,335	0	14,034	58,690	0	11,883
American	67,331	13,107	16,946	54,508	18,378	16,548	40,858	13,157	25,753	66,520	12,732	15,864
Yolo	9,125	3,403	5,011	3,931	0	4,432	5,532	0	3,561	8,912	3,538	5,697
Cosumnes-Mokelumne	0	0	1,099	0	0	1,191	0	0	1,178	0	0	572
Delta	0	0	5,164	0	0	7,703	0	0	10,198	1,617	2,848	9,226
San Joaquin	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Tulare	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Total	**445,899**	16,530	75,420	**190,591**	128,408	105,971	**158,110**	13,157	87,915	**459,126**	19,118	68,688

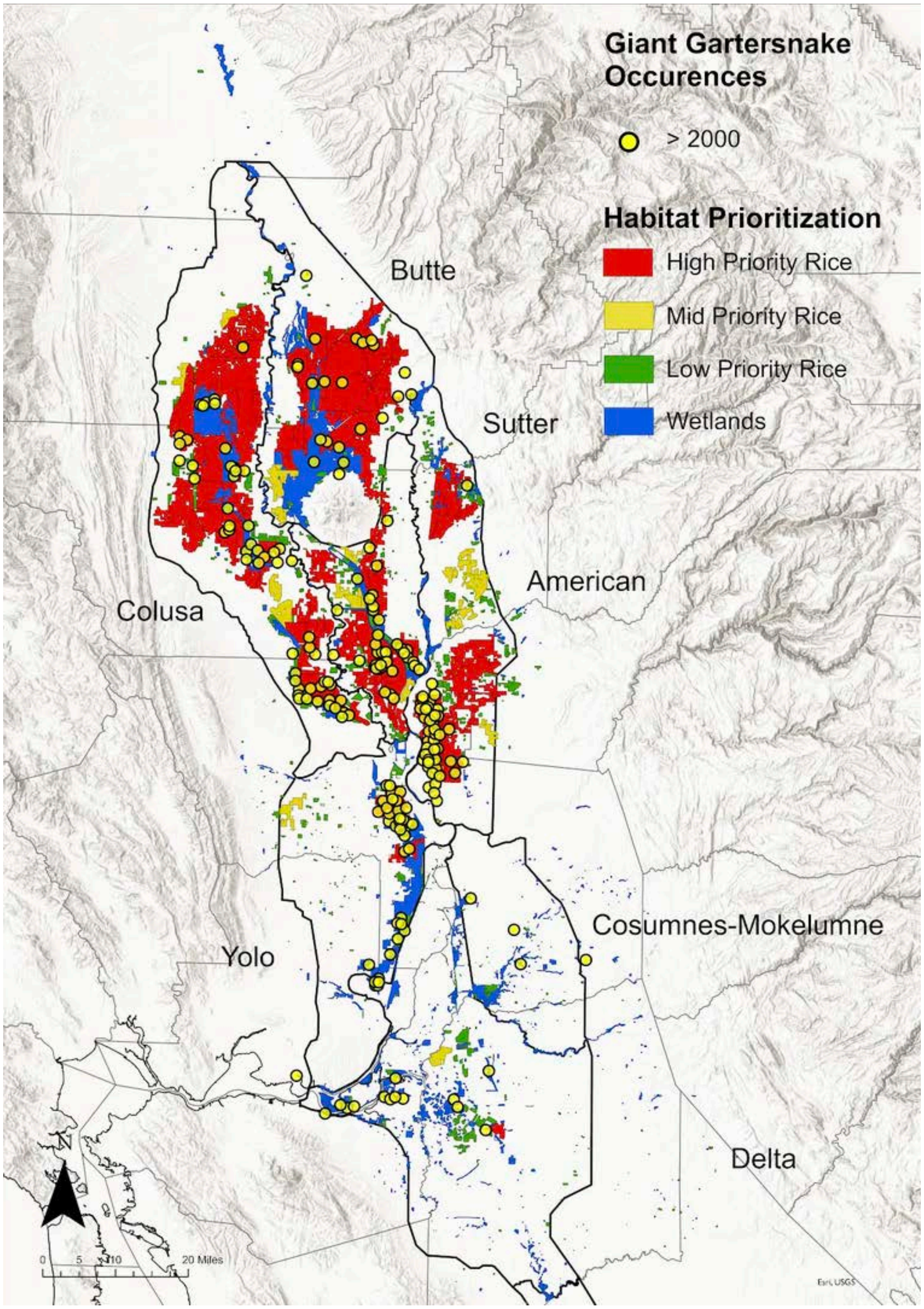

Figure 5.1.3: Map showing cultivated rice or wetland parcels in the northern Central Valley, CA from water years October 2020–September 2024. Rice was classed as either High Priority (shown in red, at least 1,578 acres in size, within 5 miles of sufficiently large wetland parcels, and having recent occurrences), Mid Priority (shown in yellow, sufficiently large and close enough to wetland parcels but lacking recent occurrences), or Low Priority (shown in green, all other rice parcels). Giant Gartersnake occurrences observed since 2000 are overlaid on the map. The occurrences were obtained from the California Natural Diversity Database queried August 2024 and managed by the California Department of Fish and Wildlife.

5.1.4 Future research

Our analyses and literature review highlighted key knowledge gaps that, if answered, could improve management of riceland for GGS populations, but need future study, including:

- **Rice Crop Consistency**: It is unclear how well GGS populations can weather the idling of ricelands in one or more years due to water transfers, droughts, or other challenges. Presumably, consistent annual deliveries of water best support GGS populations and make landscapes most suitable given the dependence of GGS on emergent aquatic vegetation and aquatic prey.
- **Improved Synchrony in Seasonal Water Availability**: As described above, the availability of water and aquatic resources like prey and vegetation have been identified as a key bottleneck in GGS survival. Presumably, changes in management that ensure adequate aquatic habitat in April each year will improve survival of GGS and benefit their populations.
- **Minimum Viable Populations**: It is currently unclear how well acreage targets for wetlands and rice agriculture blocks actually meet the space needs of a minimum viable population. Answering this question requires identifying the size of a minimum viable population and a better understanding of how space use and overlap among individuals combine with minimum population size to define minimum acreages.
- **Scope of Upland Management Impacts**: Upland areas are known to play a critical role in the active season for sheltering, basking, and thermoregulating, as well as providing critical refuge over winter. It remains unclear, however, the extent to which different types of vegetation, levee/canal management, and maintenance activities affect GGS populations. Further research is needed to quantify the types and extent of impacts of activities in upland habitat on survival and fitness.
- **Genetics and Inbreeding**: There is little information on the extent to which reduced genetic variation and connectivity among GGS populations affects demographic parameters like growth, survival, and fecundity. Understanding these dynamics and how populations are affected is critical to identify which populations may be at greatest risk and to develop strategies to enhance genetic diversity through habitat corridors or other management interventions.

Ultimately, our analysis underscores the value of ricelands for GGS populations in the Central Valley and the opportunities to improve conditions for GGS through spatial planning and studies that may reduce uncertainties in how GGS respond to riceland management. By prioritizing water management practices that align with GGS seasonal and annual needs, such as early-season flooding in irrigation canals, and focusing on the spatial arrangement of rice fields relative to wetlands, rice fields can better serve as GGS habitat. Further research on the impact of field idling, upland and riceland management practices, and the role of reduced genetic variation in isolated populations will strengthen these conservation strategies, helping balance agricultural productivity with GGS recovery (Halstead et al. 2019; Halstead et al. 2021).

5.1.5 References

Ersan, J. S. M., B. J. Halstead, E. L. Wildy, M. L. Casazza, and G. D. Wylie. 2020. Intrinsic prey preference and selection of the giant gartersnake: A threatened predator in a nonnative prey-dominated community. Journal of Fish and Wildlife Management 11:164–173.

Environmental Systems Research Institute (ESRI). 2024. ArcGIS Pro: Version 3.3.0. Redlands, CA: Environmental Systems Research Institute. https://www.esri.com/en-us/arcgis/products/arcgis-pro/overview.

Halstead, B. J., G. D. Wylie, and M. L. Casazza. 2010. Habitat suitability and conservation of the giant gartersnake (Thamnophis gigas) in the Sacramento Valley of California. Copeia 2010:591–599.

Halstead, B. J., G. D. Wylie, and M. L. Casazza. 2014. Ghost of habitat past: Historic habitat affects the contemporary distribution of giant garter snakes in a modified landscape. Animal Conservation 17:144–153.

Halstead, B. J., S. M. Skalos, G. D. Wylie, and M. L. Casazza. 2015a. Terrestrial ecology of semi-aquatic giant gartersnakes. Herpetological Conservation and Biology 10(2):633–644.

Halstead, B. J., G. D. Wylie, and M. L. Casazza. 2015b. Literature review of giant gartersnake (Thamnophis gigas) biology and conservation (Open-File Report No. 2015–1150). Open-File Report, U.S. Geological Survey.

Halstead, B. J., G. D. Wylie, M. L. Casazza, E. C. Hansen, R. D. Scherer, and L. C. Patterson. 2015c. A conceptual model for site-level ecology of the giant gartersnake (Thamnophis gigas) in the Sacramento Valley, California (Open-File Report No. 2015–1152). Open-File Report, U.S. Geological Survey.

Halstead, B. J., P. Valcarcel, G. D. Wylie, P. S. Coates, M. L. Casazza, and D. K. Rosenberg. 2016. Active season microhabitat and vegetation selection by giant gartersnakes associated with a restored marsh in California. Journal of Fish and Wildlife Management 7:397–407.

Halstead, B. J., J. P. Rose, G. A. Reyes, G. D. Wylie, and M. L. Casazza. 2019. Conservation reliance of a threatened snake on rice agriculture. Global Ecology and Conservation 19:e00681.

Halstead, B. J., P. Valcarcel, R. Kim, A. C. Jordan, J. P. Rose, S. M. Skalos, et al. 2021. A tale of two valleys: Endangered species policy and the fate of the giant gartersnake. California Fish and Wildlife Journal 264–283.

Paquin, M. M., G. D. Wylie, and E. J. Routman. 2006. Population structure of the giant garter snake, Thamnophis gigas. Conservation Genetics 7:25–36.

Reyes, G. A., B. J. Halstead, J. P. Rose, J. S. M. Ersan, A. C. Jordan, A. M. Essert, et al. 2017. Behavioral response of giant gartersnakes (Thamnophis gigas) to the relative availability of aquatic habitat on the landscape (Open-File Report No. 2017–1141). Open-File Report, U.S. Geological Survey.

Rose, J. P., J. S. M. Ersan, G. A. Reyes, K. B. Gustafson, A. M. Fulton, K. J. Fouts, et al. 2018a. Findings from a preliminary investigation of the effects of aquatic habitat (water) availability on giant gartersnake (Thamnophis gigas) demography and reproduction in the Sacramento Valley, California, 2014–17 (Open-File Report No. 2018–1114). Open-File Report, U.S. Geological Survey.

Rose, J. P., J. S. M. Ersan, G. D. Wylie, M. L. Casazza, and B. J. Halstead. 2018b. Construction and analysis of a giant gartersnake (Thamnophis gigas) population projection model (Open-File Report No. 2017–1164). Open-File Report, U.S. Geological Survey.

U.S. Fish and Wildlife Service (USFWS). 2017. Recovery plan for the giant garter snake (Thamnophis gigas). U.S. Fish and Wildlife Service, Pacific Southwest Region, Sacramento, California. vii–71.

Valcarcel, P. 2011. Giant gartersnake spatial ecology in agricultural and constructed wetlands. Oregon State University, Corvallis, Oregon, USA.

Wood, D. A., B. J. Halstead, M. L. Casazza, E. C. Hansen, G. D. Wylie, and A. G. Vandergast. 2015. Defining population structure and genetic signatures of decline in the giant gartersnake (Thamnophis gigas): Implications for conserving threatened species within highly altered landscapes. Conservation Genetics 16:1025–1039.

Wylie, G. D., M. L. Casazza, C. J. Gregory, and B. J. Halstead. 2010. Abundance and sexual size dimorphism of the giant gartersnake (Thamnophis gigas) in the Sacramento Valley of California. Journal of Herpetology 44:94–101.

5.2. A conservation footprint in California rice for non-breeding waterfowl

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Highlights

- We used the SWAMP bioenergetic model (Spatially-explicit Agent-based Waterfowl Modeling Program) to evaluate the amount and spatial distribution of rice acreage required to support duck population goals during the non-breeding season for the Central Valley.
- We developed landscape maps of rice acreage, other crops, and wetlands in the Central Valley based on historical land cover patterns representing conditions ranging from wet years with large acres of rice planted to a drought year with a drastic reduction in planted rice (Section 4). We considered alternatives when competition with geese was high and duck chronologies were delayed (HARD) versus when competition with geese was lower and duck chronologies were earlier (EASY).
- For all key metrics, a threshold of 500,000 planted acres (202,342 ha) of rice, of which 257,727 acres (104,298 ha) are winter-flooded, is necessary to ensure resilience under high-competition (HARD) conditions. Alternatively, if competition is reduced (EASY), habitat sufficiency can be achieved at 375,000 acres (151,757 ha) of planted rice, with 212,002 acres (85,794 ha) that are winter flooded. This dual-threshold approach reflects the need to balance the worst-case demands (high competition with the potential for reduced acreage) with reduced demands under favorable conditions.
- Population sizes, lipid reserves, and flight distances of ducks changed over the winter season in modeled scenarios. At 300,000 acres of planted rice, population sizes experienced steep declines (dropping below 50% of target goals by early January), lipid reserves declined rapidly by January, and average flight distances exceeded 8 km by late January, forcing ducks to travel farther to forage. Conversely, with 500,000 acres of planted rice, populations remained near 100% of the target until late February, lipid accumulation continued (with reserves peaking in mid-January and sustained through March), and average foraging flight distances were reduced by 63% (5 km).
- The model predicted that ducks would rely on rice as the dominant food item from November to early February. However, under HARD conditions, there was a sharp decline in rice consumption by mid-January, forcing a transition to seeds and invertebrates, which then comprised nearly 50% of the diet. Reduction of rice acreage and increased competition affect not only population and individual metrics of duck condition and status, but also lead to wholesale shifts in foraging ecology and diet.
- Spatial analyses identified high-priority rice fields for conservation. Proximity to roosts is a key factor influencing habitat use by waterfowl, with closer fields being more heavily utilized. High-use areas are concentrated near refuges and managed wetlands. Historical usage patterns aligned closely with model predictions, highlighting critical areas in Colusa and Butte near the major wildlife areas, as well as smaller priority areas such as the Yolo Bypass, Cosumnes, and the upper American Basin.
- Research is needed to assess the future impacts of: (i) changes in winter-flooding, (ii) increased competition with geese, (ii) shifting chronologies of duck migration, and (iv) changes in rice practices that influence the amount of residual rice grain or post-harvest field management.

5.2.1 Background and context

California's Central Valley serves as a vital wintering ground for millions of waterfowl along the Pacific Flyway (Gilmer et al. 1982, Central Valley Joint Venture 2006b, Fleskes et al. 2011, 2018) However, urban development and agricultural expansion have led to significant loss of critical wetlands habitat. Flooded rice fields now act as critical surrogates for these lost wetlands, offering essential foraging opportunities for waterfowl during the winter season (Brouder and Hill 1995, Elphick 2000, 2000, 2010, Eadie et al. 2008, Petrie et al. 2014a, Elphick et al. 2018, Central Valley Joint Venture 2020). Rice fields provide a unique habitat for waterfowl, particularly after harvest when fields are flooded. When combined with existing managed wetlands, this practice creates a mosaic of shallow water habitats with abundant seeds, waste grain, and invertebrates—key components of waterfowl diets (Miller 1987, Miller et al. 2009, Callicutt et al. 2011). Ducks rely heavily on these resources during the non-breeding period (September to late February) to build and maintain energy reserves necessary for winter survival and migration (Miller 1987, Miller et al. 1989, Reid and Heitmeyer 1995, Fleskes et al. 2009, Casazza et al. 2021). The Central Valley Joint Venture now estimates (and plans for) 50% of the food energy needed by waterfowl in winter to be provided by flooded rice (Central Valley Joint Venture 2020). The spatial distribution of flooded rice fields is equally important, as proximity to roosting sites can significantly influence foraging efficiency and energy expenditure.

Despite its critical role, the capacity of rice fields to sustain waterfowl populations is increasingly under pressure due to climate variability, economic shifts, and competing land uses (Fleskes and Perry 2005, Petrie et al. 2014a, Casazza et al. 2016, Elphick et al. 2018, 2018, Central Valley Joint Venture 2020). Several factors contribute to variability in both the quantity and quality of available habitat, impacting the resilience of waterfowl populations:

- Loss of Rice Habitat: Declines in rice acreage, particularly during drought years, reduce the availability of flooded fields, limiting foraging habitat and forcing waterfowl to travel greater distances in search of food (Fleskes et al. 2005, Fleskes and Perry 2005, Ackerman et al. 2006, Petrie et al. 2016, Iverson et al. 2024a). This can lead to increased energy expenditure and reduced lipid reserves, ultimately compromising survival and reproductive success.
- Management Practices: Variability in timing of winter flooding and water depth further affect habitat quality. Early flooding may enhance food availability, but inconsistent practices across the landscape can limit the overall effectiveness of these habitats for supporting waterfowl populations. Deep flooding limits access to foraging habitat for most ducks (Colwell and Taft 2000, Sesser et al. 2018, Behney 2020, Casazza et al. 2021). Post-harvest management of rice straw can impact the amount and accessibility of residual rice grain left remaining for foraging birds (Day and Colwell 1998, Elphick and Oring 1998, Elphick 2000, Elphick et al. 2010b, Strum et al. 2013, Matthews 2019, Matthews et al. 2022b).
- Spatial Distribution: The effectiveness of rice as habitat is closely tied to its spatial arrangement. Fields located near roosting sites or other managed wetlands are used more and have greater conservation value due to reduced travel costs and increased access to diverse food resources for the birds (Fleskes et al. 2002, 2005, 2018, Abraham et al. 2005, Ackerman et al. 2006, Overton and Casazza 2023).
- Competition with Geese: Populations of several species of geese are increasing in the Central Valley. Geese forage in both dry and wet rice fields and, with growing numbers, have potential to substantially reduce food availability for ducks in rice fields (Ackerman et al. 2006, Lefebvre et al. 2017, Cunningham et al. 2021, Skalos et al. 2021, Mott 2022). This impact is exacerbated

because geese feed in dry rice fields and so may deplete some or all waste rice grain before those fields are winter-flooded and become available to ducks.

The interplay between agricultural practices, water management, and wildlife conservation necessitates a strategic approach to habitat planning. Joint ventures, as part of the North American Waterfowl Management Plan NAWMP (U.S. Fish and Wildlife Service 2012, 2018, Humburg et al. 2018, Central Valley Joint Venture 2020), have traditionally used bioenergetic models to plan for the needs of migrating waterfowl during the non-breeding season (Miller and Eadie 2006, Baveco et al. 2011, Beatty et al. 2014, 2015, Petrie et al. 2016, Dybala et al. 2017, Ringelman et al. 2018, Central Valley Joint Venture 2020, Casazza et al. 2021, Overton and Casazza 2023). Using these models, managers determine the acreage of agricultural lands and managed wetlands required to ensure that energy supplies during fall and winter are sufficient to meet the energy demands of millions of ducks, geese and swans. New refinements to these models, such as the Spatially-explicit Waterbird Agent-based Modeling Program (SWAMP), provide more detailed spatial analysis of foraging habitat needs and enable explicit evaluation of the impacts of habitat change on metabolic demands, energy budgets, foraging distances, emigration, and survival (Miller et al. 2014, 2017, Weller et al. 2023).

Here, we use the SWAMP model to determine the rice acreage thresholds necessary to sustain waterfowl populations during the non-breeding season in the Central Valley. We did not consider the needs of rice acreage for breeding waterfowl in this analysis, lacking a comparable modeling framework. We focus on three key considerations:

1. The total acreage of flooded rice required to support target populations of ducks during fall and winter under varying conditions.
2. Spatial prioritization of rice based on proximity to roosts, usage patterns, and habitat quality.
3. The potential impacts of inter- and intra-specific competition on waterfowl foraging success and bioenergetic needs.

5.2.2 Methods

We employed the SWAMP model to simulate interactions between waterfowl, their habitats, and competitors under various scenarios. A detailed description of this model and its inputs is provided in (Miller et al. 2014, 2017, Weller et al. 2023). Several new components of this model were required for the current analysis. First, the location of roost sites is a critical element of the SWAMP program- birds are assumed to return to roost during the day and fly to foraging locations at night (Fleskes et al. 2002, 2005, Ackerman et al. 2006, Casazza et al. 2021). Working with scientists from USGS, we used extensive data from GPS telemetry locations to map roost locations. This was an important and novel advance. Second, we conducted a series of initial simulations to evaluate the effects of goose competition. We did not model geese as individual agents, but as one large agent to represent the cumulative impacts of observed populations of geese. Third, we considered variation in the chronology of duck migration. Large populations of ducks remaining later in the winter more heavily impact resource availability at a time when resources have been depleted and are more limited. These important additions to the SWAMP model are described and presented in detail in Appendix A.2. Using these analyses, we were then able to develop habitat scenarios that represent a realistic range of conditions that reflect these uncertainties. A final critical component of this analysis, independent of revisions to the SWAMP model, was the development of a comprehensive integrative mapping process described in Section 4.

Habitat scenarios: We modeled 14 habitat scenarios, varying rice acreage between 254,000 and 526,000 acres, to isolate the influence of habitat availability. Scenarios were developed based on historical land cover patterns from 2021-2022 and 2023-2024, systematically adjusting acreage based on the likelihood of rice being grown in given parcels. In general, the lowest acreage scenarios tended to only include parcels which were very often rice, while higher acreage scenarios included parcels which were less often rice. Additional details on building these habitat scenarios are available in Appendix A.2.

Roost Sites: Telemetry data on high-value roosting sites provided critical spatial anchors for foraging and energy dynamics. 500 roosting sites were selected for use in the agent-based model, which accounted for 67.2% of the individual roosting points within the dataset (despite accounting for only 5% of the total map area). 84.1% of the selected roost sites were within wetlands or rice fields. The chosen roost sites and their location relative to different land cover types are shown in Figure 5.2.1. Details on roost site selection methods are provided in Appendix A.2.

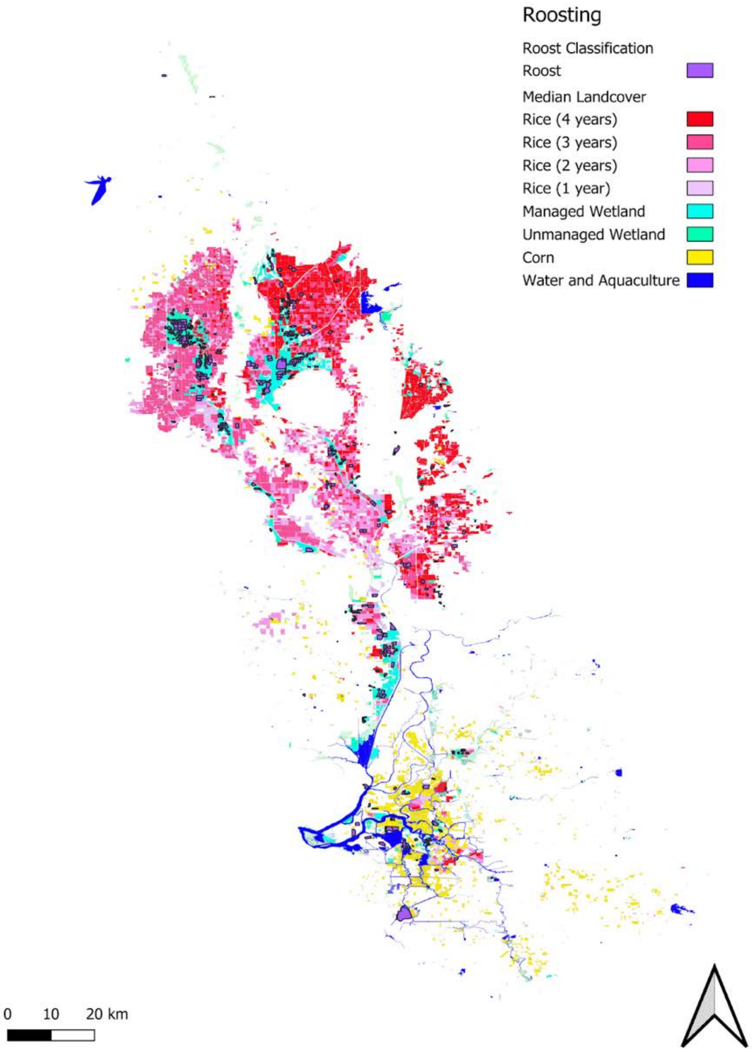

Figure 5.2.1. Roost Locations and Surrounding Land Cover. This map displays the spatial distribution of identified high-value roosting sites (purple) within the Central Valley and the surrounding land cover types relevant to the SWAMP model. The classification includes median land cover for rice across four years (red to light pink gradients), managed and unmanaged wetlands (cyan and teal), corn (yellow), and water and aquaculture (blue). Roost sites are primarily located near rice fields and wetlands, highlighting their importance in providing accessible habitat for waterfowl. The clustering of roosts near high-density rice fields and managed wetlands underscores the critical role these areas play in supporting energy balance and minimizing travel distances for foraging.

Competition: Alternative goose competition and population chronologies were explored in preliminary analyses (see Appendix A.2). Here, we explore key metrics (below) across habitat scenarios with 'High Competition' (Geese receive 100% of their energy from rice and corn resources and duck populations are delayed and remain until later in the season) as well as 'Low Competition' (Geese receive some of their energy from alternative resources and duck chronology is shifted earlier in the season, reducing competition when resources are scarce) treatments. These treatments represent alternative plausible competition scenarios with different environmental and management conditions, as well as representing some scientific uncertainty.

Key Metrics: We assessed how different rice acreage scenarios influence key population and habitat metrics. Here, we focus on three of the most informative metrics: Days to Deficit (DTD), Total Duck Use Days (DUD), and Total Duck Energy (TDE).

- ***Days to Deficit (DTD****):* This measures the number of days before average individual net energy becomes negative, signaling that food resources have become limiting.
- ***Total Duck Use Days (DUD*****):** This represents a cumulative measure of habitat use across the winter season, reflecting how effectively available habitat supports duck populations.
- ***Total Duck Energy (TDE):*** This measures the combined lipid reserves of ducks emigrating from the Central Valley and those remaining at the end of the season, excluding individuals that die. It reflects the population's readiness for migration and breeding, with higher values indicating that individuals are better able to successfully migrate to breeding grounds, arrive with sufficient energy to reproduce, and support long-term population sustainability.

Together, these metrics are critical for determining whether rice acreage supports target waterfowl populations under current conditions and aligns with Central Valley Joint Venture (CVJV) conservation objectives. Each metric provides somewhat different information about the status of the population and demonstrates that single metrics used by many Joint Ventures – such as Duck Use Days – may not fully represent the condition or state of the birds. We also examined population dynamics, lipid reserves, foraging flight distances, and diet composition to provide insights into within season dynamics. These are provided in Appendix A.2.

Rice Acreage Thresholds*:* For each of three core metrics detailed above, we assessed the minimum rice acreage (including representative amounts of winter flooding) required to sustain wintering duck populations. Each acreage scenario was categorized based on its ability to meet sufficiency thresholds under both high- and low-competition conditions:

- GREEN: Metrics exceed sufficiency thresholds for both demanding and less-demanding conditions.
- YELLOW: Metrics only exceed sufficiency thresholds for less-demanding conditions.
- RED: Metrics are below sufficiency thresholds for both conditions.

The sufficiency threshold for each metric was determined based on the acreage value at which that metric approached an asymptote under high-competition conditions (see Appendix A.2 for details). This approach was chosen to identify the point at which increasing rice acreage no longer produced substantial gains in duck population health or habitat sufficiency, effectively providing a conservative estimate of what is required to meet the needs of the population under the most challenging conditions. The asymptote indicates the point of diminishing returns— where additional rice acreage has minimal added benefit. This conservative threshold ensures that the habitat can sustain duck populations at or near target levels, even during years with higher competition. It is important to note that these thresholds do not necessarily define the minimum amount of habitat that could be acceptable; rather, they identify the level of habitat that fully supports population needs without significant further benefit from additional acreage.

5.2.3 Results

Total Rice Acreage: Unsurprisingly, more rice acreage is needed to sustain waterfowl under high competition scenarios. Figure 5.2.2 illustrates the relationship between rice acreage and each of the three metrics—Days to Deficit (DTD), Total Duck Use Days (DUD), and Total Duck Energy (TDE)— across varying scenarios, highlighting critical thresholds for habitat sufficiency. Under high-competition (HARD) conditions, DTD plateaued at in early-February (~160 days) when rice acreage reached 500,000 acres. Lower competition (EASY) conditions achieved this same threshold with

450,000 acres. Similarly, DUD and TDE exhibited asymptotic behavior, where sufficiency was reached at 500,000 acres under HARD scenarios and at ~375,000 acres for DUD and ~350,000 acres for TDE under EASY scenarios.

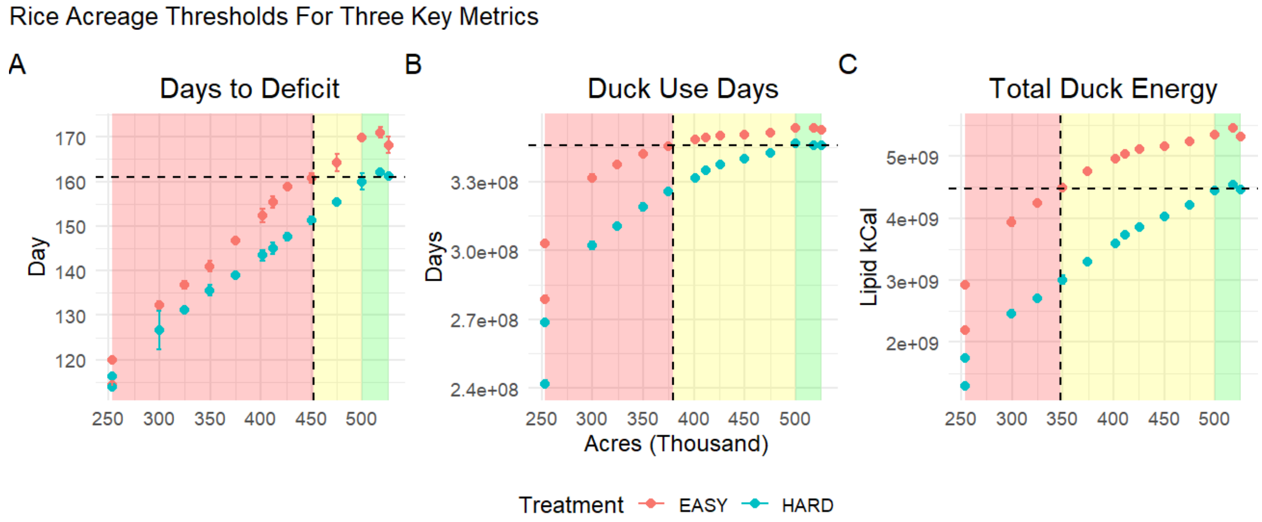

Figure 5.2.2. Rice Acreage Thresholds Under Hard – High Competition (RED) and EASY – Low Competition (BLUE) for three key metrics. (A) **Days to Deficit:** The number of days until the food supply becomes insufficient to meet the energy needs of the wintering duck population. (B) **Duck Use Days:** The cumulative number of days waterfowl spend in the Central Valley, reflecting habitat usage. (C) **Total Duck Energy:** The combined energy state of ducks at the end of the wintering period, including lipid reserves of resident and emigrant ducks. The vertical dashed line indicates thresholds critical for achieving sufficiency, while the horizontal dashed line marks the asymptote of each metric under High Competition. Shaded regions highlight scenarios of insufficiency (red), transition (yellow), and sufficiency (green).

These findings reveal two potential thresholds for habitat sufficiency. For all three metrics, a threshold of 500,000 acres is necessary to ensure resilience under high-competition conditions (GREEN), providing a robust buffer against variability in competition and environmental factors. Alternatively, if competition is reduced, habitat sufficiency can be achieved at 350,000–375,000 acres (YELLOW) for DUD and TDE, which each provide a holistic account of population health over the course of the season. Below the lower threshold, all key metrics decline rapidly under all scenarios. This dual-threshold approach reflects the need to balance the worst-case demands of high competition with the potential for reduced acreage sufficiency under favorable conditions

Seasonal Energy Needs and Population Metrics*:* To further explore the impact of habitat availability, we examined how waterfowl populations, lipid reserves, and flight distances changed over the winter season (Figure 5.2.3) in sufficient (GREEN, 500,000 rice acres), marginal (YELLOW, 400,000 acres), and insufficient (RED, 300,000 acres) rice acreage scenarios. These temporal dynamics revealed stark differences between scenarios, highlighting the interactions between sufficiency levels and competition:

- Population Targets: In GREEN scenarios, populations remained near 100% of the target until late February under both EASY and HARD conditions. Conversely, RED scenarios experienced a steep decline, with populations dropping below 50% by early January under HARD conditions, reflecting severe habitat insufficiency.

- Lipid Reserves: GREEN scenarios supported robust lipid accumulation, with reserves peaking in mid-January and sustaining through March. These reserves provide individuals with the necessary energy for migration and subsequent breeding success. In RED scenarios, lipid reserves declined rapidly by January, exacerbating vulnerability to energy deficits and reducing survival rates.
- Flight Distances: Insufficient acreage forced ducks to travel farther to forage, significantly increasing energy expenditure. Average flight distances exceeded 8 km by late January in RED scenarios, compared to 5 km in GREEN scenarios. This added strain underscores the cascading effects of inadequate habitat.

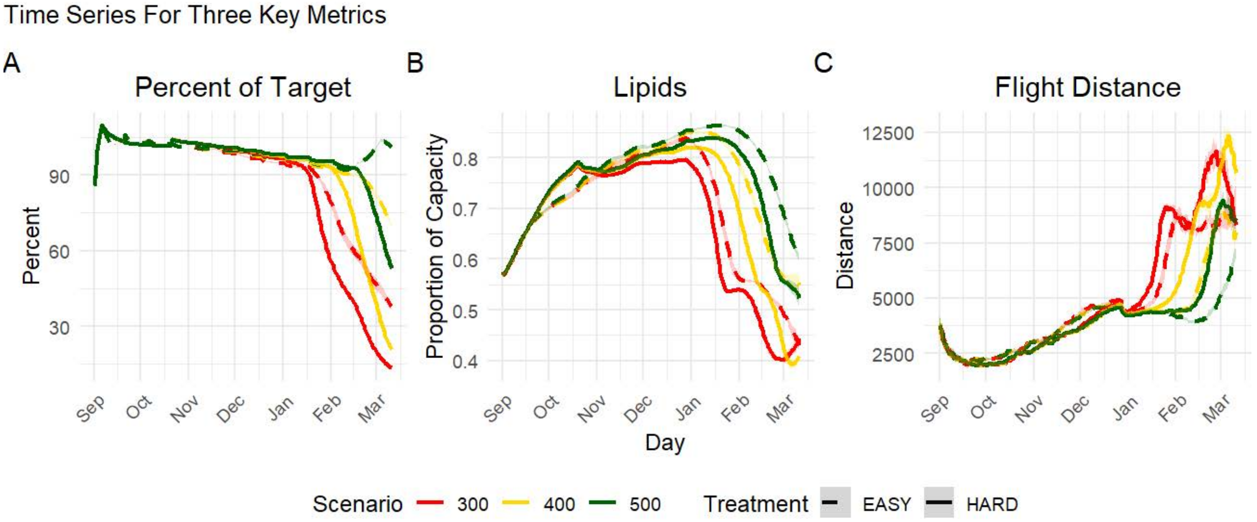

Figure 5.2.3. Time Series for Three differences Key Metrics Across Rice Acreage Scenarios and Competition Treatments**. (A) Percent of Target:** The percentage of the target waterfowl population sustained throughout the winter, illustrating in population retention under EASY – Low competition (solid lines) and HARD – High Competition (dashed lines) competition treatments. Scenarios with 300,000 acres (red), 400,000 acres (yellow), and 500,000 acres (green) of rice are shown. **(B) Lipids**: The average proportion of lipid capacity maintained by waterfowl, indicating individual energy reserves under different scenarios and treatments. (**C) Flight Distance**: Average foraging flight distance (meters) per individual over time, demonstrating the effect of habitat availability and competition on waterfowl movement dynamics. The plots highlight the seasonal patterns of energy dynamics and the effects of habitat sufficiency on population resilience and behavior

Diet Composition and Resource Shifts: Resource availability and competition also influence diet composition, as shown in Figure 5.2.4. Waterfowl rely on rice, seeds, and invertebrates at different stages of the season, with notable shifts under varying scenarios. In GREEN scenarios, rice served as the dominant dietary component from November to early February, providing a critical energy source. Under HARD competition, diets in RED scenarios exhibit a sharp decline in rice contributions by mid-January, forcing a transition to alternative, less energy-dense food sources.

As rice availability diminished, seeds and invertebrates became increasingly important dietary components. By late February, under HARD conditions, these resources comprise nearly 50% of the diet. This shift underscores how habitat insufficiency alters dietary patterns, with potential long-term implications for individual health and survival

These dietary dynamics illustrate the adaptability of waterfowl in response to habitat conditions, but also underscore the limitations imposed by insufficient acreage. Reduction of rice acreage and increased competition (especially by geese), influence not only population and individual metrics of condition and status but are also reflected in wholesale shifts in foraging ecology and diet – patterns that may fall under the radar without focused analysis.

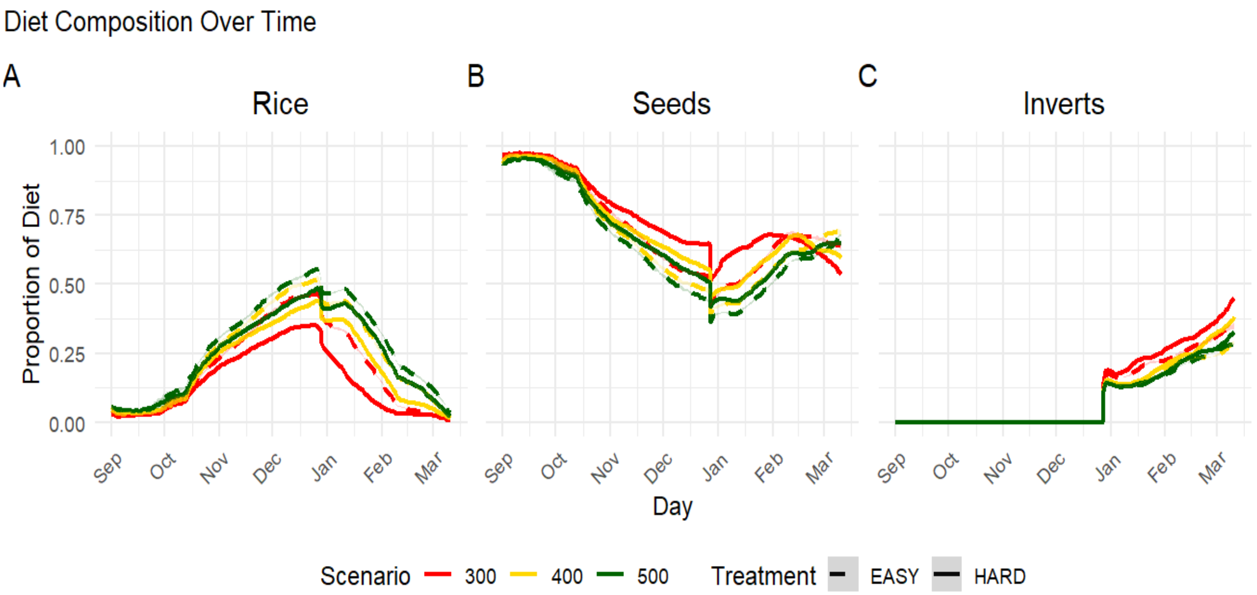

Figure 5.2.4. Diet Composition Over Time Across Rice Acreage Scenarios and Competition Treatments. **(A)** Proportion of diet composed of rice, **(B)** proportion of diet composed of seeds, and **(C)** proportion of diet composed of invertebrates. Trends are shown for three rice acreage scenarios (300,000, 400,000, and 500,000 acres) under two competition treatments (EASY and HARD). Solid lines indicate EASY - Low Competition, while dashed lines represent HARD – High Competition.

Spatial Prioritization: A critical aspect of managing rice acreage to sustain wintering duck populations in California's Central Valley involves spatial prioritization— identifying which areas of rice should be prioritized to maximize ecological benefits, particularly under constraints like limited water availability and increasing competition for food resources. To achieve this, we integrated multiple spatial data layers to assess patterns of habitat use and highlight rice patches that contribute most to sustaining waterfowl populations.

This analysis incorporated both modeled and observed data to ensure a comprehensive prioritization approach. Model-predicted usage was evaluated at the foraging area level under three scenarios representing different levels of total rice acreage—300,000 (RED), 400,000 (YELLOW), and 500,000 (GREEN) acres. In parallel, empirical data on actual waterfowl use were analyzed at both the individual patch scale and broader foraging area scale to reflect real-world habitat selection patterns. While distance to roost sites was not explicitly included as a prioritization factor, it is inherently reflected in usage patterns; roost sites themselves are often among the most heavily utilized areas or are closely associated with high-use foraging patches.

The resulting **combined spatial prioritization** map (Figure 5.2.5) synthesizes these datasets into a unified framework, classifying rice patches based on their relative importance for waterfowl. A given patch is designated as high priority if it is consistently identified as such in ANY (high priority, red) or ALL (highest priority, black) of the three components—model predicted foraging area use, observed patch-level use, or observed foraging-area use. Low priority patches (in green), are those which were identified as low priority across all components. This integrative approach highlights areas that are critical either due to their demonstrated importance for foraging or their predicted value in supporting habitat needs under varying landscape conditions.

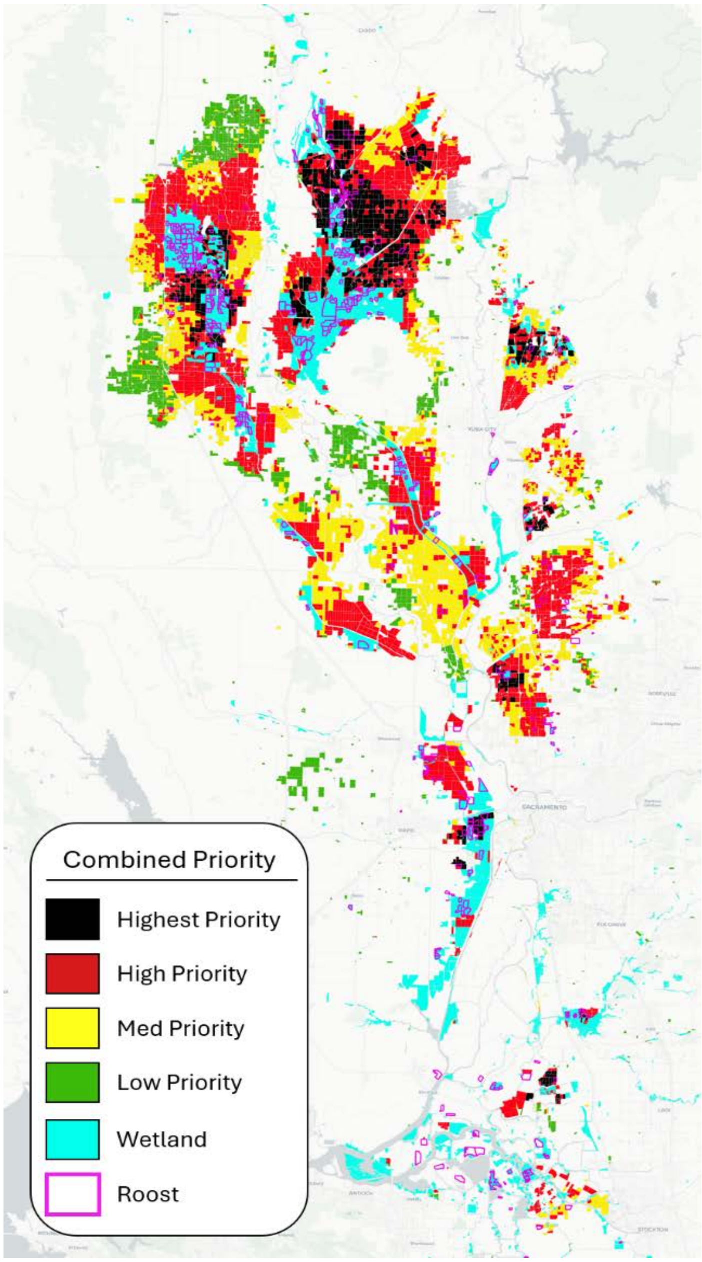

Figure 5.2.5. Combined priority map of rice fields for wintering waterfowl in California's Central Valley. Priority levels are based on model-predicted and observed usage across multiple scenarios. **Black areas** indicate the highest-priority patches, while **red, yellow, and green** represent decreasing priority levels. Wetlands (**cyan**) and roost sites (**magenta outlines**) are included for context but were not directly incorporated into the prioritization algorithm. However, their proximity to high-priority patches highlights their importance in structuring waterfowl habitat use. This map highlights broad spatial trends for conservation and management planning rather than prescriptive field-level recommendations.

The prioritization analysis reveals strong spatial trends that align with ecological principles governing waterfowl foraging behavior. High-priority areas are concentrated around wetlands, refuges, and established roost sites, reinforcing the importance of minimizing energy expenditure associated with foraging flights. Key regions that emerge as conservation focal points include the Colusa and Butte Basins, where both observed and modeled data consistently indicate high use, as well as the Yolo Bypass and Cosumnes River regions, which serve as critical but more localized foraging areas. The upper American Basin also ranks as an area of moderate priority, particularly under higher acreage scenarios.

Lower-priority patches tend to be located along the peripheries of major basins or in areas farther from roosts. While these fields may provide some habitat value, their relative importance for sustaining large populations is reduced due to the increased energy costs associated with foraging flights. However, lower-priority does not necessarily mean low value—

these areas may still play an important role in habitat connectivity and as supplemental resources under certain environmental conditions.

The combined results from Figure 5.2.5 demonstrate the critical importance of spatial prioritization in habitat management for waterfowl. Fields near roosts and refuges consistently emerge as high-value habitats, while distant or isolated fields hold limited conservation value. The observed usage trends validate the predictive power of the agent-based model, which effectively highlights the areas that require conservation focus under varying acreage scenarios. Ultimately, management strategies should aim to maintain or enhance rice fields in these high-priority zones to maximize habitat benefits for waterfowl while optimizing limited resources. Efforts to improve habitat quality in lower-priority fields, such as through staggered flooding schedules or creating new roost sites, could also help expand usable habitat and reduce pressure on the most utilized areas

5.2.4 Future Research and Management

Winter-flooding: **For waterfowl, the critical threshold is not just planted rice acreage, but rather the proportion that is winter-flooded** and thus available to ducks for foraging. Ducks require a minimum of 212,000–258,000 acres of winter-flooded rice at the January water peak, with depths between 1 and 10 inches to be accessible (ideally 4-8 inches). Accordingly, it will be critical to continue to maintain support for winter-flooding of rice fields during fall and winter. There is now considerable research on the effect of harvest management on use of rice fields by waterfowl and shorebirds (see Table 1.1 Introduction). However, future changes in post-harvest practices, such as baling, deep disking, or dry field straw incorporation, could impact the value of rice fields in winter for waterfowl and other waterbirds. Ongoing research and incentives will be required to maintain sufficient winter-flooded acreage for conservation needs.

Competition with geese: **Large and growing goose populations** (notably Snow, Ross's and White-fronted Geese) **will have significant impacts on the availability of residual rice grain for ducks.** Our analyses revealed large effects of goose competition on the rice acreage thresholds needed to sustain sufficient food resources for ducks. This would be exacerbated if fewer fields are winter-flooded because geese readily forage in dry fields, whereas most ducks in the Central Valley do not. Hence, a reduction in flooding would not only reduce forageable acres for ducks but once flooded, the residual rice grain may already be depleted by geese that used the area prior to the onset of flooding. Additional research on the impacts of geese is needed, but this is likely to be a larger scale challenge, dealing with the causes of burgeoning goose populations at a flyway scale. Efforts to reduce or redistribute goose populations to reduce competition with ducks within the Central Valley, particularly in dry fields prior to winter flooding, would be helpful but the means to do so is unclear.

Shifting chronologies of waterfowl migration: **The timing of arrival in the fall and departure in the spring will further impact the value of rice acreage**. Our analyses show that if birds arrive earlier, when food resources are abundant, the long-term impacts on carrying capacity are lower than if birds arrive later when resources are depleted (see Appendix A.2). One suggestion is that staggered flooding schedules could help to prolong habitat availability, ensuring that some areas remain accessible throughout the critical winter months. For example, delaying some flooding until late winter might maximize food availability during critical periods and ensure resources are available when food scarcity is most acute. Counter to this, however, is the risk that leaving fields dry longer in the fall would expose those fields to goose foraging, eliminating any benefit and perhaps making the situation worse. Other wildlife (e.g. blackbirds, rodents) also feed on rice grain in dry fields, further reducing food resources. Research is needed to explore these tradeoffs to explore schedules of flood-up that could maximize late-season food resources for ducks while minimizing competition with geese.

Other rice management practices: Finally, research would be valuable on rice management practices that leave more residual grain available for foraging ducks. For example, deep disking or chiseling may leave less residual rice grain than chopping, baling, or no treatment at all (Matthews 2019, Matthews et al. 2022b). However, it is not known if post-harvest treatments also impact foraging efficiency of birds such that even if more grain is available, it may be less accessible under a heavy mat of rice straw. Straw management could also influence invertebrate production, especially in late winter. Our analyses suggest that invertebrates comprise an important source of energy for ducks in late winter when rice grain and other seeds are depleted. This may provide a new avenue by which to increase late winter food resources for waterfowl and shorebirds. The importance of invertebrates in the diets and carrying capacity of ducks in California deserves more attention. Further consideration should also be given to enhancing the quality of marginal or lower-priority rice fields through habitat modifications, such as adding roost sites or improving connectivity to existing wetlands.

5.2.5 References

Abraham, K. F., R. L. Jefferies, and R. T. Alisauskas. 2005. The dynamics of landscape change and snow geese in mid-continent North America. Global Change Biology 11:841–855.

Ackerman, J. T., J. Y. Takekawa, D. L. Orthmeyer, J. P. Fleskes, J. L. Yee, and K. L. Kruse. 2006. Spatial Use by Wintering Greater White-Fronted Geese Relative to a Decade of Habitat Change in California’s Central Valley. Journal of Wildlife Management 70:965–976.

Baveco, J. M., H. Kuipers, and B. A. Nolet. 2011. A large-scale multi-species spatial depletion model for overwintering waterfowl. Ecological Modelling 222:3773–3784.

Beatty, W. S., E. B. Webb, D. C. Kesler, L. W. Naylor, A. H. Raedeke, D. D. Humburg, J. M. Coluccy, and G. J. Soulliere. 2015. An empirical evaluation of landscape energetic models: Mallard and American black duck space use during the non-breeding period: Waterfowl Energetic Carrying Capacity. The Journal of Wildlife Management 79:1141–1151.

Beatty, W. S., E. B. Webb, D. C. Kesler, A. H. Raedeke, L. W. Naylor, and D. D. Humburg. 2014. Landscape effects on mallard habitat selection at multiple spatial scales during the non-breeding period. Landscape Ecology 29:989–1000.

Behney, A. C. 2020. The influence of water depth on energy availability for ducks. The Journal of Wildlife Management 84:436–447.

Brouder, S., and J. Hill. 1995. Conjunctive use of farmland adds value: Winter flooding of ricelands provides waterfowl habitat. California Agriculture 49:58–64.

Callicutt, J. T., H. M. Hagy, and M. L. Schummer. 2011. The Food Preference Paradigm: A Review of Autumn–Winter Food Use by North American Dabbling Ducks (1900–2009). Journal of Fish and Wildlife Management 2:29–40.

Casazza, M. L., F. McDuie, S. Jones, A. A. Lorenz, C. T. Overton, J. Yee, C. L. Feldheim, J. T. Ackerman, and K. M. Thorne. 2021. Waterfowl use of wetland habitats informs wetland restoration designs for multi-species benefits. Journal of Applied Ecology 58:1910–1920.

Casazza, M. L., C. T. Overton, T.-V. D. Bui, J. M. Hull, J. D. Albertson, V. K. Bloom, S. Bobzien, J. McBroom, M. Latta, P. Olofson, T. M. Rohmer, S. Schwarzbach, D. R. Strong, E. Grijalva, J. K. Wood, S. M. Skalos, and J. Takekawa. 2016. Endangered species management and ecosystem restoration: finding the common ground. Ecology and Society 21:art19.

Central Valley Joint Venture. 2006. Central Valley Joint Venture Implementation Plan: Conserving Bird Habitat. U.S. Fish and Wildlife Service, Sacramento, California, USA.

Central Valley Joint Venture. 2020. Central Valley Joint Venture 2020 Implementation Plan. U.S& Wildlife Service, Sacramento, CA.

Colwell, M. A., and O. W. Taft. 2000. Waterbird communities in managed wetlands of varying water depth. Waterbirds 23:45–55.

Cunningham, S. A., Q. Zhao, and M. D. Weegman. 2021. Increased rice flooding during winter explains the recent increase in the Pacific Flyway White-fronted Goose *Anser albifrons frontalis* population in North America. Ibis 163:231–246.

Day, J. H., and M. A. Colwell. 1998. Waterbird communities in rice fields subjected to different post-harvest treatments. Waterbirds 21:185–197.

Dybala, K. E., M. E. Reiter, C. M. Hickey, W. D. Shuford, K. M. Strum, and G. S. Yarris. 2017. A bioenergetics approach to setting conservation objectives for non-breeding shorebirds in California’s Central Valley. San Francisco Estuary and Watershed Science 15.

Eadie, J., C. Elphick, K. Reinecke, and M. Miller. 2008. Wildlife values of North American ricelands. Pages 7–90 Conservation in Ricelands of North America: Current State of Our Knowledge and a Course for Future Research and Education. The Rice Foundation, Stuttgart, AR.

Elphick, C. 2000. Functional equivalency between rice fields and seminatural wetland habitats. Conservation Biology 14:181–191.

Elphick, C. 2010. Why study birds in rice fields? Waterbirds 33:1–7.

Elphick, C., T. R. Kelsey, Hickey, Catherine, P. Buttner, Strum, Khara, and Iglecia, Monica. 2018. Wetland bird conservation in california rice fields. Pages 293–296 Cranes and Agriculture: A Global Guide for Sharing the Landscape. Minuteman Press, Baraboo, Wisconsin.

Elphick, C. S., and L. W. Oring. 1998. Winter management of Californian rice fields for waterbirds. Journal of Applied Ecology 35:95–108.

Elphick, C., O. Taft, and P. M. Loureno. 2010. Management of rice fields for birds during the non-growing season. Waterbirds 33:181–192.

Fleskes, J. P., M. L. Casazza, C. T. Overton, E. L. Matchett, and J. L. Yee. 2018. Changes in the abundance and distribution of waterfowl wintering in the Central Valley of California, 1973–2000. Pages 50–74 Trends and Traditions: Avifaunal Change in Western North America. Western Field Ornithologists.

Fleskes, J. P., R. L. Jarvis, and D. S. Gilmer. 2002. Distribution and movements of female Northern Pintails radiotagged in San Joaguin Valley, California. Journal of Wildlife Management 66:138–152.

Fleskes, J. P., E. L. Matchett, L. E. Flint, M. Petrie, and M. Reiter. 2011. Understanding impacts of climate change on ecology and habitats of waterfowl, shorebirds, and other waterbirds: Guidance for the California LCC and other wetland habitat conservation programs in the Pacific Flyway. Progress Update: Data Summary., USGS Western Ecological Research Center, Sacramento, California.

Fleskes, J. P., M. R. Miller, G. S. Yarris, D. R. Thomas, and J. M. Eadie. 2009. Increased winter habitat improves body condition of ducks in the Central Valley of California. Page 5th North American Duck Symposium. Available: http://www. northamericanducksymposium. org/docs/fleskes_ oral. pdf (June 2012).

Fleskes, J. P., and W. M. Perry. 2005. Change in area of winter-flooded and dry rice in the northern central valley of California determined by satellite imagery. Califonia Fish and Game 91:207–215.

Fleskes, J. P., J. L. Yee, M. L. Casazza, M. R. Miller, J. Y. Takekawa, and D. L. Orthmeyer. 2005. Waterfowl distribution, movements, and habitat use relative to recent habitat changes in the Central Valley of California: A cooperative project to investigate impacts of the Central Valley Joint Venture and changing agricultural practices on the ecology of wintering waterfowl. Final Report, U.S. Geological Survey-Western Ecological Research Center, Dixon Field Station, Dixon, California.

Gilmer, D. S., M. R. Miller, R. D. Bauer, and J. R. Ledonne. 1982. California’s Central Valley Wintering Waterfowl: Concerns and Challenges California’s Central Valley Wintering Waterfowl: Concerns and Challenges. US Fish & Wildlife Publications. 41.

Humburg, D. D., M. G. Anderson, M. G. Brasher, M. F. Carter, J. M. Eadie, D. C. Fulton, F. A. Johnson, M. C. Runge, and M. P. Vrtiska. 2018. Implementing the 2012 North American Waterfowl Management Plan revision: Populations, habitat, and people. The Journal of Wildlife Management 82:275–286.

Iverson, S. A., C. M. Hickey, and K. A. Sesser. 2024. Minimizing Impacts and Increasing Opportunity for Wildlife due to Rice Fallowing and Rotation in the Sacramento Valley. Central Valley Joint Venture, Point Blue Conservation Science (Contribution No. 2516), Petaluma, CA.

Lefebvre, J., G. Gauthier, J. F. Giroux, A. Reed, E. T. Reed, and L. Bélanger. 2017. The greater snow goose Anser caerulescens atlanticus: Managing an overabundant population. Ambio 46:262–274.

Matthews, L. 2019. Changing post-harvest practices, impacts on waste grain availability, and growers’ perspectives. Master’s Thesis., University of California Davis, Davis, California, USA.

Matthews, L. J., M. Petrie, and J. M. Eadie. 2022. Impacts of Changing Postharvest Agricultural Practices on Abundance of Waste Grain in California’s Central Valley. Journal of Fish and Wildlife Management 13:320–333.

Miller, M. L., K. M. Ringelman, J. M. Eadie, and J. C. Schank. 2017. Time to fly: A comparison of marginal value theorem approximations in an agent-based model of foraging waterfowl. Ecological Modelling 351:77–86.

Miller, M. L., K. M. Ringelman, J. C. Schank, and J. M. Eadie. 2014. SWAMP: An agent-based model for wetland and waterfowl conservation management. SIMULATION 90:52–68.

Miller, M. R. 1987. Fall and Winter Foods of Northern Pintails in the Sacramento Valley, California. The Journal of Wildlife Management 51:405.

Miller, M. R., E. G. Burns, B. E. Wickland, and J. M. Eadie. 2009. Diet and Body Mass of Wintering Ducks in Adjacent Brackish and Freshwater Habitats. Waterbirds 32:374–387.

Miller, M. R., and J. M. Eadie. 2006. The allometric relationship between resting metabolic rate and body mass in wild wintering waterfowl (Anatidae) and an application to estimation of winter habitat requirements. The Condor 108:166–177.

Miller, M. R., D. E. Sharp, D. S. Gilmer, and D. Mulvaney. 1989. Rice Available to Waterfowl in Harvested Fields in The Sacramento Valley, California. California Fish and Game 75:113–123.

Mott, A. L. 2022. Habitat use and distribution implications of four goose species wintering in California's Sacramento valley. Master's Thesis, University of California, Davis, Davis, California, USA.

Overton, C. T., and M. L. Casazza. 2023. Movement behavior, habitat selection, and functional responses to habitat availability among four species of wintering waterfowl in California. Frontiers in Ecology and Evolution 11:1232704.

Petrie, M., M. G. Brasher, and D. James. 2014. Estimating the biological and economic contributions that rice habitats make in support of North American Waterfowl. The Rice Foundation, Stuttgart, Arkansas, USA.

Petrie, M. J., J. P. Fleskes, M. A. Wolder, C. R. Isola, G. S. Yarris, and D. A. Skalos. 2016. Potential effects of drought on carrying capacity for wintering waterfowl in the central valley of california. Journal of Fish and Wildlife Management 7:408–422.

Reid, F., and M. Heitmeyer. 1995. Sidebar: Waterfowl and rice in California's Central Valley. California Agriculture 49:62–62.

Ringelman, K. M., C. K. Williams, P. M. Castelli, M. L. Sieges, R. A. Longenecker, T. C. Nichols, and S. D. Earsom. 2018. Estimating Waterfowl Carrying Capacity at Local Scales: A Case Study from Edwin B. Forsythe National Wildlife Refuge, New Jersey1. Journal of Fish and Wildlife Management 9:106–116.

Sesser, K. A., M. Iglecia, M. E. Reiter, K. M. Strum, C. M. Hickey, R. Kelsey, and D. A. Skalos. 2018. Waterbird response to variable-timing of drawdown in rice fields after winter-flooding. PLOS ONE 13:e0204800.

Skalos, D. A., J. M. Eadie, D. R. Yparraguirre, M. L. Weaver, S. L. Oldenburger, C. R. Ely, J. L. Yee, and J. P. Fleskes. 2021. Body Condition of Wintering Pacific Greater White-Fronted Geese. The Journal of Wildlife Management 85:484–497.

Strum, K. M., M. E. Reiter, C. A. Hartman, M. N. Iglecia, T. R. Kelsey, and C. M. Hickey. 2013. Winter management of California's rice fields to maximize waterbird habitat and minimize water use. Agriculture, Ecosystems & Environment 179:116–124.

U.S. Fish and Wildlife Service. 2012. North American Waterfowl Management Plan 2012 Revision: People Conserving Waterfowl and Wetlands.

U.S. Fish and Wildlife Service. 2018. North American Waterfowl Management Plan (NAWMP) 2018 update: connecting people, waterfowl, and wetlands. North American Waterfowl Management Plan, Place of publication not identified.

Weller, F. G., E. B. Webb, S. Fogenburg, W. S. Beatty, D. Kesler, R. H. Blenk, K. M. Ringelman, M. L. Miller, C. Arzel, and J. M. Eadie. 2023. An agent-based model to quantify energetics, movement and habitat selection of mid-continent mallards in the Mississippi Alluvial Valley. Ecological Modelling 485:110488.

5.3 Black Terns & Shorebirds

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Highlights

- Rice provides important habitat to wetland-dependent birds year-round, including nearly 100% of the Central Valley breeding habitat for Black Tern, a California Bird Species of Special Concern, and more than half of the food energy supply needed to support the large, diverse community of shorebirds over the non-breeding season.
- Changes in the footprint of planted rice can directly affect tern and shorebird breeding population sizes and the risk of local extirpation or loss of genetic diversity.
- Changes in the extent of winter-flooded rice and fallowed rice affect the magnitude and timing of energy shortfalls for shorebirds during the nonbreeding season.
- The estimated rice footprint needed to support shorebird and Black Tern conservation targets is based on the best available research, but further research on Black Tern ecology and benthic invertebrate productivity could identify opportunities for best management practices to support these species more effectively with fewer acres.

5.3.1 Background and context

The wetland-dependent bird community in California's Central Valley is large and diverse, varying seasonally as migratory species arrive and depart throughout the year. During the spring and summer breeding season (peaking mid-April through mid-July), a small population of Black Tern (*Chlidonias niger*; a California Bird Species of Special Concern) nests in the Central Valley, along with thousands of shorebirds, including three other Central Valley Joint Venture (CVJV) focal species: Black-necked Stilt (*Himantopus mexicanus*; hereafter Stilt), American Avocet (*Recurvirostra americanus*; hereafter Avocet), and Killdeer (*Charadrius vociferous*; Shuford and Dybala 2017; Shuford and Gardali 2008; Strum et al. 2017). During the lengthy nonbreeding season (approximately 1-July through 15-May), at least 19 shorebird species regularly rely on the Central Valley for foraging habitat during migration and over the winter (Shuford et al. 1998; Dybala et al. 2017). The Central Valley population of 9 of these species is expected to be of primary importance relative to the rest of the United States (Hickey et al. 2003), and 12 of these species have national conservation status designations in the U.S. Shorebird Conservation Plan (USCPP 2015). The size of the nonbreeding shorebird community is estimated to vary from approximately 50,000 individuals at each end of the season (July and May) up to 500,000 individuals during the peak of spring migration in March and April (Dybala et al. 2017a).

Use of Rice: During the breeding season, rice farms provide suitable nesting habitats for all four-breeding season focal species (Shuford et al. 2016; Strum et al. 2017). Recent survey efforts estimated 90% of all Black Terns nesting in the Central Valley were in the Sacramento Valley, all of which were in rice (Shuford et al. 2016). In addition, 98% of Stilt nests and 93% of Avocet nests in the Sacramento Valley were found in rice farms (Shuford et al. 2007). Surveys within rice farms found that all Black Tern nests and the majority of Stilt nests were within rice fields themselves, while Avocet was more likely to nest on levees (Iglecia et al. 2014). During the non-breeding season, shorebirds forage for benthic invertebrates in shallow-flooded water, especially in managed seasonal wetlands and postharvest-flooded rice fields (including fields that had been fallowed the previous growing season; Dybala et al. 2017a). The depth limit for foraging habitat depends on the species, but many do not forage in water >10 cm (4 inches) deep (Dybala et al. 2017a and citations therein). Despite these depth limitations, winter-flooded rice (and fallowed rice) contribute a large proportion of the total acreage of shallowly-flooded habitat in the Central Valley that is accessible to most shorebirds, and, although rice fields have a lower estimated food energy density (calories per acre of benthic invertebrates) compared to wetlands, on average rice is estimated to contribute more than half of the annual food energy supply consumed by the shorebird community throughout the nonbreeding season (Dybala et al. 2017a).

Conservation needs: Rice and other flooded agriculture help offset the loss of over 90% of the Central Valley's historic wetlands (Frayer et al. 1989), but the population sizes of wetland-dependent birds are still likely to be limited by the availability of suitable nesting and foraging habitat (CVJV 2020; Dybala et al. 2017a; Shuford and Dybala 2017; Strum et al. 2017). The population sizes of all four breeding seasons focal species are declining in the Central Valley (Strum et al. 2017; Shuford et al. 2016). During the nonbreeding season, shortfalls in the food energy supply available to shorebirds are estimated to occur in most years during the fall and spring "shoulder" portions of the nonbreeding season (Dybala et al. 2017a; Golet et al. 2022), with implications for body condition, survival, and subsequent reproductive success and flyway-scale population trends. Consequently, the Central Valley Joint Venture has established long-term population and habitat restoration objectives to increase the extent of high-quality habitat to support larger, more resilient populations (Shuford and Dybala 2017; Strum et al. 2017; Dybala et al. 2017a). While the CVJV's implementation plan primarily calls for increasing the extent of habitat provided by managed wetlands, it also assumed the average footprint of habitat provided by rice in recent years (2007-2014) will remain stable and continue to contribute to habitat. Any loss of rice, especially conversion to other unsuitable crops, would result in further loss of habitat for these wetland dependent species, contributing to further population declines.

5.3.2 Methods

To estimate the impacts of a variable extent of rice habitat on Black Tern and shorebirds, we analyzed 5 scenarios representing data from 4 recent water years (Fall 2020–Spring 2024) with a simulated 5th water year representing the relatively dry 2022-2023 year without the unusually extensive spring rain (see Section 4). For the breeding season, we evaluated the total extent of breeding habitat available in planted rice and managed wetlands in each scenario and estimated regional breeding population sizes for Black Tern, Stilt, and Avocet based on previous estimates of average breeding densities (Shuford et al. 2016; Strum et al. 2017; no comparable estimates were available for Killdeer). We evaluated these population size estimates using a framework developed to guide the establishment of CVJV conservation objectives, in which breeding population sizes under 1,000 individuals are considered "very small" and at increased risk of loss of genetic diversity and local extirpation (Dybala et al. 2017b). To inform the rice footprint needed during the breeding season, we estimated thresholds for the footprint of planted rice required to maintain a Central Valley breeding population of Black Tern above 1,000 individuals and to meet the CVJV population objective of doubling the recent Black Tern population size (approximately 3,984 individuals; Shuford et al. 2016; Dybala and Shuford 2017).

For shorebirds during the nonbreeding season, we evaluated the extent of foraging habitat available across all suitable land cover classes, including seasonal managed wetlands and winter-flooded rice and fallowed rice. Using the CVJV's population objectives for nonbreeding shorebirds, we fit a shorebird bioenergetics model to each of the 5 scenarios to estimate the timing and magnitude of any shortfalls in food supply between the daily energy needs of the shorebird community and the daily food energy available and accessible to shorebirds across all suitable land cover classes

(Dybala 2016; Dybala et al. 2017a). We compared the results from each scenario to identify the influence on energy shortfalls of varying rice footprints and, for the two versions of 2022-2023, the influence of extensive spring rain.

We applied existing models and spatial data to conduct a spatial prioritization analysis among parcels ever planted with rice in 2020-2024 using Zonation 5 software (Moilanen et al. 2022). For breeding season data, we used the most recently available county-specific estimates of Black Tern densities in rice (Shuford et al. 2016; Iverson 2024) together with predicted estimates of habitat suitability for Stilt and Avocet during the edges of the breeding season (April and July, due to data limitations), based on recently developed distribution models (Conlisk et al.2022). For the nonbreeding season, we used predicted habitat suitability during the peak of the nonbreeding season (Nov, Dec, Jan) for Stilt, Avocet, and two additional taxa for which distribution models were available: Dunlin (*Calidris alpina*) and a combined model for Long-billed and Short-billed Dowitcher (*Limnodromus griseus* and *L. scolopaceus*). For each season, we used the CAZ1 variant of the Core Area Zonation algorithm to rank rice pixels according to their relative ability to provide suitable habitat to the most species, giving Black Tern double the weight of other species due to its status as a Bird Species of Special Concern. We grouped rice parcels in the top 20% (>0.8) as relatively high priority and parcels in the bottom 50% as relatively low priority. See Appendix A.3 for additional methods details.

5.3.3 Results

Across scenarios, the estimated footprint of planted rice in the Sacramento and Yolo-Delta planning regions ranged from a low of 102,598 ha (253,526 ac) in 2022 to 212,769 ha (525,763 ac) in 2023 (Figure 5.3.1A). In every scenario, the footprint of planted rice was lower than the previous average estimated over the same geography, 2007-2014 (217,246 ha; 536,826 ac; Dybala et al. 2017a; Strum et al. 2017). The midwinter peak footprint of flooded rice and fallow rice was also lower than the original CVJV estimate in every scenario; the closest occurred in 2022-2023 with extensive spring rain (Figure 5.3.1B). The variation in the rice footprint mirrored variation in estimated breeding population sizes, with the largest populations for each species in 2020-2021 and 2023-2024 and the smallest in 2022-2023 (Figure 5.3.2). Notably, the estimated Black Tern population dropped below the threshold of 1,000 individuals for a “very small” population in both 2021-2022 and 2022-2023.

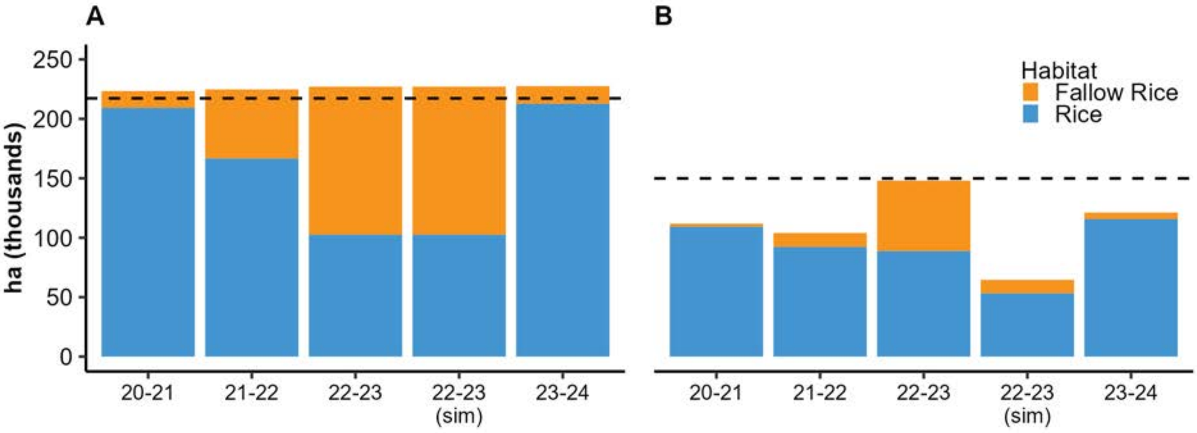

Figure 5.3.1: Rice footprints by scenario. **(A)** Total footprint of planted and fallow rice. **(B)** Peak footprint of winter flooded rice. Dashed lines represent the average footprints provided during 2007-2014 that were assumed to remain stable in CVJV conservation objectives.

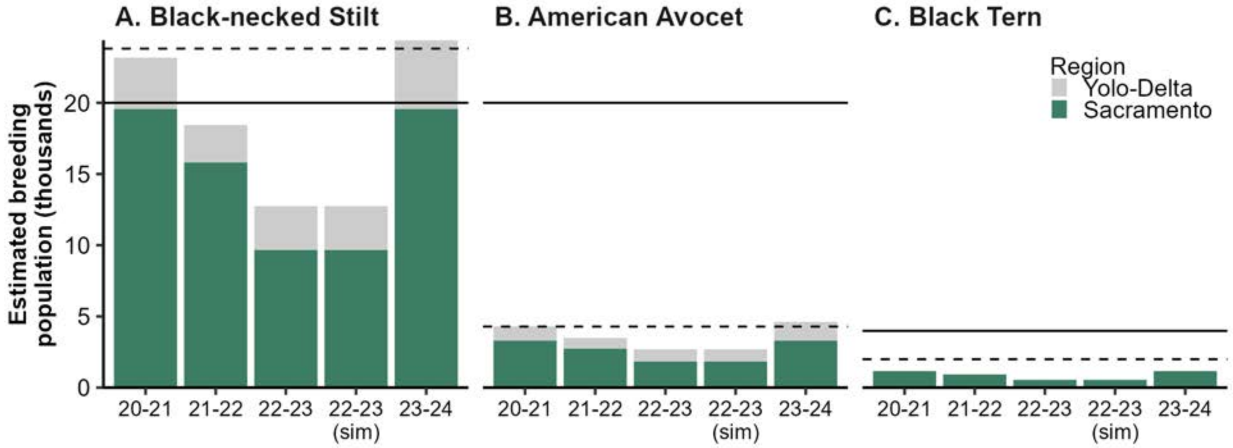

Figure 5.3.2: Estimates of regional breeding population size by scenario and CVJV planning region. (A) Black-necked Stilt. (B) American Avocet. (C) Black Tern. Dashed lines represent recent population estimates and solid lines represent the CVJV's long-term population objectives for Sacramento and Yolo-Delta regions combined.

Based on the recent average breeding density of 0.58 birds per 100 ha, a rice footprint of >172,414 ha (426,043 ac) is needed to maintain a Black Tern population above 1,000 individuals, reducing the risk of local extirpation and loss of genetic diversity (Table 5.3.1). However, if habitat quality could be enhanced to restore breeding densities to the prior estimate of 1.8 birds per 100 ha (Shuford et al. 2001), a rice footprint of > 191,333 ha (472,794 ac) may be sufficient to meet the CVJV's long-term population objective for Black Tern, provided flooding is maintained throughout the entire breeding season (see Rice Management Priorities section below). A rice footprint of this size would also contribute to maintaining a breeding Stilt population that meets CVJV objectives and would continue to provide substantial breeding habitat for Avocet. Using these thresholds to define "red", "yellow", and "green" rice footprints, 2020-2021 and 2023-2024 were both "green", while 2021-2022 and 2022-2023 were both "red".

Table 5.3.1. Proposed thresholds for evaluating the impact of a changing footprint of planted rice on breeding population sizes. For the nonbreeding season, we also defined a separate target for the midwinter peak of flooded rice and fallowed rice of 151,167 ha (373,540 ac; equivalent to dashed line in Fig. 5.3.1B; see text for details).

GREEN **> 191,333 ha (472,794 ac)**	**YELLOW** **> 172,414 ha (426,043 ac) and < 191,333 ha (472,794 ac)**	**RED** **< 172,414 ha (426,043 ac)**
May be sufficient to meet long-term CVJV population objectives for Black Tern, if breeding densities can be improved.	Insufficient to meet Black Tern population objectives, but likely sufficient to maintain a breeding population above the threshold of 1,000 individuals.	High risk of the Black Tern breeding population falling below 1,000 individuals, with increased risk of local extirpation and loss of genetic diversity.

For nonbreeding shorebirds, there were energy shortfalls during the fall and spring "shoulder" portions of every scenario, with a magnitude and timing that were similar to previous analyses (Figure 5.3.3; Dybala et al. 2017a; Golet et al. 2022). Fall shortfalls were concentrated in July to mid-October in each scenario, and were lowest in 2020-2021 and 2023-2024, the two "green" scenarios with the highest amounts of planted rice. Spring shortfalls fell primarily in late-February to mid-May and were similar in magnitude across scenarios except for the two versions of 2022-2023. Extensive winter rain substantially reduced spring shortfalls, while the simulated absence of that rain and a greatly reduced extent of winter-flooded rice (Figure 5.3.1B) resulted in increased consumption pressure in managed wetlands and larger "spring" shortfalls that spanned January to mid-May. Thus, even though shortfalls in energy supply primarily occur outside the time frame when rice is typically flooded in winter, shorebird habitat provided by winter-flooded rice fields can reduce the consumption pressure in managed wetlands through the winter, leaving more food remaining in wetlands and reducing spring energy shortfalls.

The rice footprint needed to support nonbreeding shorebirds depends on the extent that is winter-flooded and can include winter-flooded fallow rice fields. Therefore, in addition to the thresholds for planted rice proposed in Table 5.3.1, we propose a threshold for the midwinter peak of flooded rice and fallowed rice of 151,167 ha (373,540 ac), equivalent to the average midwinter peak that was previously estimated in developing the CVJV conservation objectives (2007-2014; dashed line in Figure 5.3.1B; Dybala et al. 2017a). A winter-flooded rice footprint above this threshold would support nonbreeding shorebird conservation objectives in the CVJV implementation plan by maintaining the substantial contributions of rice to shorebird habitat, while footprints below this threshold would increase pressure on managed wetlands. This target includes an assumption that most of the winter-flooded acres are maintained throughout the winter, accounts for the relatively small proportion of these flooded acres that are accessible to most foraging shorebirds (<10 cm depth) and includes the best-available estimates of the density and energy content of benthic invertebrates in winter-flooded rice. Changes in water management or new practices to increase invertebrate production could change the number of acres needed. Additional shallow flooding that directly targets spring and fall shortfall periods, such as through incentive programs, is another valuable way rice fields can provide habitat to nonbreeding shorebirds (Golet et al. 2022).

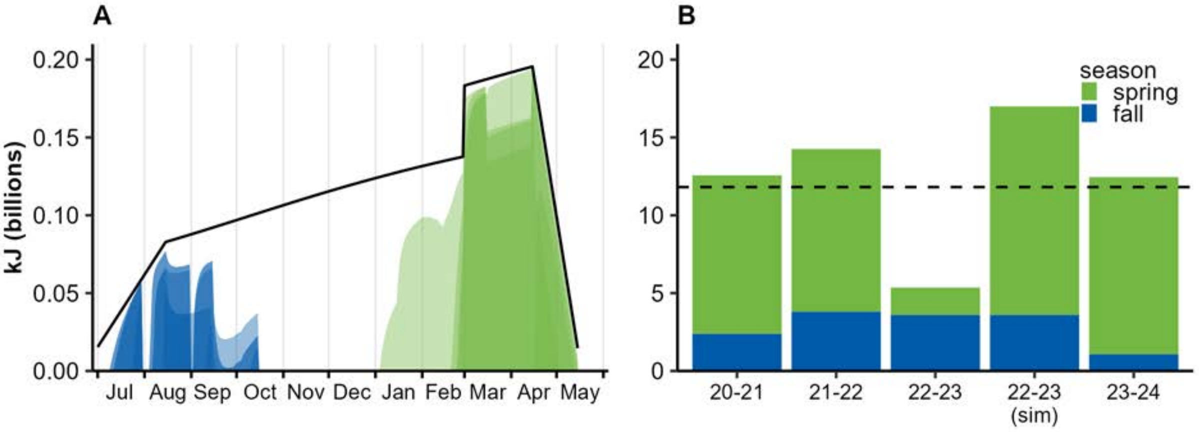

Fig. 3: Estimated energy shortfalls during the fall and spring "shoulders" of the nonbreeding season. **(A)** Timing and magnitude of daily shortfalls, shown with translucent fill so darker areas represent more consistent shortfalls across scenarios. The solid line represents the daily energy requirement that must be met to support the long-term population objectives (the maximum energy shortfall that could be estimated). **(B)** Seasonal shortfall totals in each scenario, shown with a dashed line representing the average shortfalls estimated by the CVJV, which conservation objectives are trying to eliminate.

Spatial Priorities: Breeding densities in rice were highest in the Yolo-Delta region for both Stilt and Avocet, while for Black Tern, densities were highest in the Sacramento region, especially Glenn and Yuba counties in 2010 (Shuford et al. 2016; Strum et al. 2017; Iverson et al. 2024). The spatial prioritization for the breeding season reflected these patterns, with the largest blocks of relatively high priority rice in Glenn and Yuba counties (Figure 5.3.4). During the nonbreeding season, relatively high priority areas were more dispersed throughout. However, the high priority areas represent only 20% of the rice footprint in 2020-2024, while at least 73% is needed to prevent the Black Tern breeding population falling below 1,000 individuals and at least 81% is needed to support Black Tern conservation objectives (Table 5.3.1). Thus, all of the high and moderate priority areas and a large proportion of the low priority areas are important to these species.

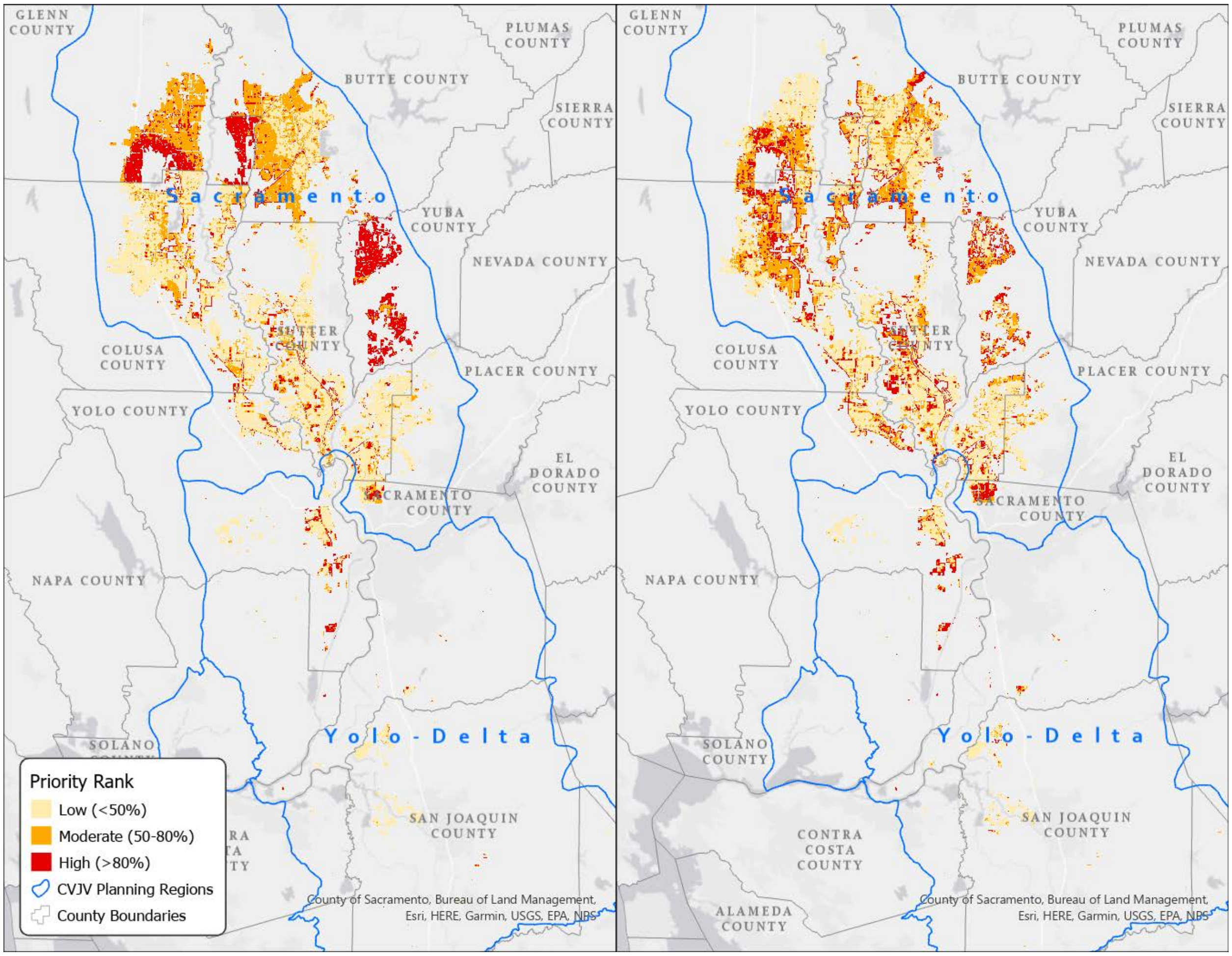

Fig. 5.3.4: Spatial prioritization results in rice for breeding shorebirds (left) and nonbreeding shorebirds (right).

Rice management priorities: During the breeding season, water levels should be maintained consistently to avoid destroying active nests when water levels are raised and limit access by nest predators (e.g., rats) when fields are drained (Shuford et al. 2001; Shuford and Dybala 2017). In addition, small islands can be installed or berms widened to create more suitable nest substrate (Strum et al. 2014). During the nonbreeding season (1 July—mid-May), foraging habitat for shorebirds must be flooded, without dense vegetation, and not too deep (ideally <10cm or 4in; Dybala et al. 2017; Conlisk et al. 2024). The bioenergetics model assumes an average proportion of winter-flooded rice that is <10 cm depth each day (Dybala et al. 2017a), such that a widespread change in "typical" winter flooding schedules and depths that reduces this proportion (such as deeper flooding to provide fish habitat) would also reduce shorebird foraging habitat. Conversely, slowing the rate of flood-up and drawdown, staggering the timing across fields, or introducing additional periods of flooding during the fall and spring shoulder seasons (such as through incentive programs) can provide more suitable habitat for shorebirds (Strum et al. 2014; Sesser et al. 2018; Golet et al. 2022). In addition, management practices that incorporate rice straw and stubble into the soil to promote decomposition are associated with increased shorebird abundance (Sesser et al. 2016), may increase invertebrate densities (Lawler and Dritz 2005), and could have the added benefit of improving the ability of shorebirds to probe into otherwise heavy clay soils (Conlisk et al. 2024).

5.3.4 Future Research Directions

To avoid further declines of the already small Central Valley Black Tern population and identify opportunities to enhance habitat quality and increase breeding densities, research is needed on their ecology, habitat requirements, and population demography, including reproductive success, movements with changing water conditions, and diet (Shuford 2008; Shuford et al. 2016; Iverson et al. 2024). Similar studies of factors driving reproductive success in Stilt and Avocet populations would also be beneficial (Strum et al. 2017). For nonbreeding shorebirds, research on the ecology of benthic invertebrates could identify opportunities to manage for increased productivity, which could allow supporting more birds on fewer acres.

5.3.5 References

[CVJV] Central Valley Joint Venture. 2020. Central Valley Joint Venture 2020 Implementation Plan. U.S. Fish and Wildlife Service, Sacramento, CA. https://www.centralvalleyjointventure.org/science/2020-implementation-plan.

Conlisk, E. E., G. H. Golet, M. Reynolds, N. Elliott, and M. E. Reiter. 2024. Factors influencing shorebird use of post-harvest flooded rice fields in California's Sacramento Valley. The Journal of Wildlife Management 88:e22661. doi:10.1002/jwmg.22661.

Dybala, K. E. 2016. bioenergmod: Bioenergetics Modeling. R package 0.1.0. https://github.com/kdybala/bioenergmod

Dybala, K. E., M. E. Reiter, C. M. Hickey, W. D. Shuford, K. M. Strum, and G. S. Yarris. 2017a. A bioenergetics approach to setting conservation objectives for non-breeding shorebirds in California's Central Valley. San Francisco Estuary and Watershed Science 15:2. doi:10.15447/sfews.2017v15iss1art2.

Dybala, K. E., N. Clipperton, T. Gardali, G. H. Golet, R. Kelsey, S. Lorenzato, R. Melcer Jr, N. E. Seavy, J. G. Silveira, and G. S. Yarris. 2017. A general framework for setting quantitative population objectives for wildlife conservation. San Francisco Estuary and Watershed Science 15:8. doi:10.15447/sfews.2017v15iss1art8.

Golet, G. H., K. E. Dybala, M. E. Reiter, K. A. Sesser, M. Reynolds, and R. Kelsey. 2022. Shorebird food energy shortfalls and the effectiveness of habitat incentive programs in record wet, dry, and warm years. Ecological Monographs. doi:10.1002/ecm.1541.

Hickey, C. M., G. W. Page, W. D. Shuford, and S. Warnock. 2003. Southern Pacific Shorebird Conservation Plan: A strategy for supporting California's Central Valley and coastal shorebird populations. PRBO Conservation Science, Stinson Beach, California. Version 1.0. http://www.prbo.org/cms/docs/wetlands/SPSCPlan_010904.pdf.

Iglecia, M. N., K. L. Velas, T. R. Kelsey, J. A. Dhundale, C. S. Shake, and M. A. Hardy. 2014. Year 2 Summary of Shorebird Nesting Habitat Enhancement Study. Audubon California, Sacramento, CA.

Iverson, A. R., C. Hickey, and K. Sesser. 2024. Rice fallowing and wildlife: Minimizing impacts and increasing opportunity for wildlife due to rice fallowing and rotation in the Sacramento

Valley. Report to the Central Valley Joint Venture. Point Blue Conservation Science, Petaluma, CA.

Lawler, S. P., and D. A. Dritz. 2005. Straw and winter flooding benefit mosquitoes and other insects in a rice agroecosystem. Ecological Applications 15:2052–2059. doi:10.1890/03-5420.

Sesser, K. A., M. Iglecia, M. E. Reiter, K. M. Strum, C. M. Hickey, R. Kelsey, and D. A. Skalos. 2018. Waterbird response to variable-timing of drawdown in rice fields after winter-flooding. PLOS ONE 13:e0204800. doi:10.1371/journal.pone.0204800.

Sesser, K. A., M. E. Reiter, D. A. Skalos, K. M. Strum, and C. M. Hickey. 2016. Waterbird response to management practices in rice fields intended to reduce greenhouse gas emissions. Biological Conservation 197:69–79. doi:10.1016/j.biocon.2016.02.021.

Shuford, W. D. 2008. Black Tern (*Chlidonias niger*). In: W. D. Shuford, T. Gardali, editors. *California Bird Species of Special Concern: a ranked assessment of species, subspecies, and distinct populations of birds of immediate conservation concern in California*. Studies of Western Birds 1. Western Field Ornithologists, Camarillo, California, and California Department of Fish and Game, Sacramento, California; p. 193–198.

Shuford, W. D., K. Sesser, K. M. Strum, D. B. Haines, and D. A. Skalos. 2016. Numbers of Terns Breeding Inland in California: Trends or Tribulations? Western Birds 47:182–213. doi:10.21199/WB47.3.1.

Shuford, W. D., and K. E. Dybala. 2017. Conservation objectives for wintering and breeding waterbirds in California's Central Valley. San Francisco Estuary and Watershed Science 15:4. doi:10.15447/sfews.2017v15iss1art4.

Shuford, W. D., and T. Gardali. 2008. California Bird Species of Special Concern: A ranked assessment of species, subspecies, and distinct populations of birds of immediate conservation concern in California. Western Field Ornithologists, Camarillo, California, and California Department of Fish and Game, Sacramento, California. https://wildlife.ca.gov/Conservation/SSC/Birds.

Shuford, W., J. Humphrey, and N. Nur. 2001. Breeding status of the Black Tern in California. Western Birds 32:189–217. https://www.westernfieldornithologists.org/archive/V32/32(4)p0189-p0217.pdf

Shuford, W. D., G. W. Page, and J. E. Kjelmyr. 1998. Patterns and dynamics of shorebird use of California's Central Valley. Condor 100:227–244. doi:10.2307/1370264.

Strum, K. M., K. E. Dybala, M. N. Iglecia, and W. D. Shuford. 2017. Population and habitat objectives for breeding shorebirds in California's Central Valley. San Francisco Estuary and Watershed Science 15:3. doi:10.15447/sfews.2017v15iss1art3.

Strum, K. M., K. Sesser, and M. N. Iglecia. 2014. Waterbird Habitat Enhancement Program: Bird-friendly farming in California rice fields. California Rice Commission. http://calrice.org/pdf/waterbirdhabitatbro_web.pdf.

[USSCPP] U.S. Shorebird Conservation Plan Partnership. 2016. U.S. Shorebirds of Conservation Concern - 2016. U.S. Fish and Wildlife Service, Washington, D.C. http://www.shorebirdplan.org/science/assessment-conservation-status-shorebirds/

5.4 Sandhill Cranes

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Highlights

- Sandhill Cranes hold special conservation status in California. The Greater subspecies is state-listed as threatened and the Lesser subspecies as a species of special concern.
- The vast majority of California's cranes winter in the Sacramento Valley and the Yolo-Delta Region. They make substantial use of rice farms for both foraging (unflooded conditions) and roosting (flooded conditions).
- To accommodate cranes at recommended roosting densities, we estimate 43,139 acres of flooded rice is needed in November to complement other potential roosting habitat. Lower acreage is needed in other months (Oct-Mar) because of fewer birds or more extensive additional flooded habitat.
- A mix of shallowly flooded and unflooded rice would do the most to support cranes' needs for roosting and foraging habitat in close proximity.
- Providing this habitat in the Yolo-Delta Region is a high priority because of high bird numbers and generally high roost suitability there.

5.4.1 Background and context

Every year, tens of thousands of Sandhill Cranes (*Antigone canadensis*) join the throngs of waterbirds that winter in California's Central Valley. Their numbers pale in comparison to millions of ducks and geese, yet cranes command special attention. These large, loud, and gregarious birds are celebrated at an annual crane festival and sought out by wildlife photographers and birders. Further, the two subspecies that predominate are afforded special conservation status: the Greater Sandhill Crane (*A. c. tabida*) is state-listed as threatened, and the Lesser Sandhill Crane (*A. c. canadensis*) is state-listed as a species of special concern.

Numbers of both subspecies swell in September and October as southbound migrants conclude their journeys (Pogson and Lindstedt 1991, Donnely et al. 2021). They comingle in open wetland, grassland, and farmland habitats of California's Central Valley for the winter, and most depart by April (Ivey et al. 2016). During this non-breeding period, cranes usually subsist on farmed cereal grains and other plant foods which are supplemented by small amounts of animal prey (Gerber et al. 2020). Birds aggregate in shallow, open water for nighttime roosting (Ivey et al. 2014).

Despite journeying hundreds or even thousands of kilometers to spend the winter in California (Littlefield and Thompson 1982, Donnely et al. 2021), once cranes arrive, they are rather sedentary. Flights between roosts and foraging grounds averaged just 1.9 km (1.2 mi; Greater subspecies) to 4.5 km (2.8 mi; Lesser subspecies) for cranes wintering in the Sacramento-San Joaquin Delta (Ivey et al. 2015). Satellite-based tracking studies in Southern California and Arizona concluded that roosting and foraging grounds should be in close proximity (<5 km (3.1 mi) apart) to best support cranes (Collins et al. 2023). Thus, there is clear justification to frame Sandhill Crane conservation in terms of "habitat complexes" (Ivey et al. 2014). The ideal complex includes foraging habitat, which is usually drier and more agricultural, closely adjoined to roosting habitat, which is consistently flooded. Rice fields have the potential to fit well into the habitat complex concept, so it is important to consider the extent of rice farming and the choice of rice farming practices in the endeavor to conserve California's cranes.

Use of Rice & Considerations: Depending on field management, cranes may use rice farms for both foraging and roosting. Studies of digestive tract contents have confirmed that cranes forage on rice directly (Lewis 1974, Ballard and Thompson 2000). Harvested but otherwise unaltered rice stubble was identified as the most important land cover for cranes foraging in California's Butte Basin, though they had a higher preference for newly planted wheat fields, when available (Littlefield 2002). A follow-up study in the same region confirmed that rice was the primary foraging habitat and that cranes foraged more in rice that was not tilled or deeply flooded (Shasky 2012). Cranes foraging in rice fields have also been observed taking snails, aquatic weed tubers, and other foods typical of the rice agroecosystem (Lewis 1974). When fields are more deeply and consistently flooded, use may shift from foraging to roosting. Cranes selected water depths averaging 15.5 cm (6.1 in) for roosting in one study (Shaskey 2012) and 10 cm (3.9 in) in another (Ivey et al. 2014). Wetlands provided important roosting habitat, but in California's Delta Region, cranes roosted at even higher densities in flooded agricultural fields (Ivey et al. 2014).

Lower rice cultivation or changing management practices could negatively impact cranes. In a compilation of Sandhill Crane diet studies (Gerber et al. 2020), cereal grains were the most important food item across a variety of landscapes and populations, and the maintenance of productive farmland is a key priority from a bioenergetic perspective (Pearse et al. 2010, Boggie et al. 2023). Management decisions related to flooding shape whether rice will primarily support foraging or roosting, and a mix of both grainfields and flooded areas would be most consistent with the habitat complex concept and habitat selection models (Donnely et al. 2021). In one study of cranes in the Delta Region, densities of cranes were higher in flooded rice than other habitats, even among non-roosting birds (Shuford et al. 2019). This suggests an intriguing possibility that certain flooding conditions could serve needs beyond nighttime roosting. Finally, cranes are often highly faithful to wintering sites, and the four main wintering regions in California's Central Valley have not changed markedly for decades (Ivey et al. 2016). Thus, maintenance of rice habitat where it has historically been used by cranes would seem poised to support future, recurrent use.

5.4.2 Methods

To estimate the amount of rice needed to support Sandhill Cranes, we focused on roosting habitat because Sandhill Crane roosting needs have been specifically and quantitatively identified (Ivey et al. 2014, Veloz et al. 2017). Our approach consisted of: (1) Using a literature review and survey data to estimate a target population size, (2) Quantifying roost habitat needs versus availability under five different landscape scenarios, and (3) Identifying the rice parcels most suitable to serving as crane roosts based on a previously developed roost habitat suitability model.

Population Estimate & Objectives: The California Department of Fish and Wildlife (CDFW) has conducted the Central Valley Midwinter Waterfowl Survey in its present form since 2016; methods differed prior. Each January, a period between long-distance migration, Sandhill Cranes are counted along aerial transects spread throughout waterfowl habitat (i.e., farmland and wetlands that are commonly flooded in winter) in the Central Valley, substantially overlapping known hotspots of crane abundance (Fig. 5.4.1).

We estimated crane abundance based on the average counts from all years since 2016 for which data were available using an intercept-only generalized linear model with a Tweedie distribution, appropriate for count data (Bonat et al. 2018). We reviewed the literature for additional estimates of Sandhill Crane abundance in the Central Valley and for quantitative population recovery objectives. Finally, to account for seasonal shifts in crane abundance and to generate monthly population estimates and objectives, we used eBird indices of abundance calculated for cranes observed in counties overlapping the Sacramento Valley and/or Yolo-Delta Regions (Fig. 5.4.2). Indices of abundance were converted to z-scores to account for variable scales and units,

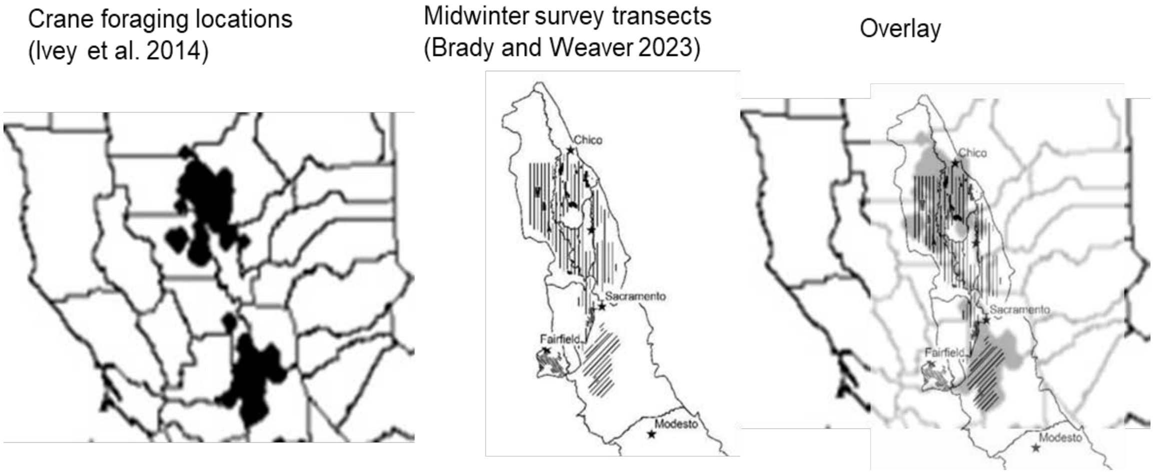

Figure 5.4.1. Approximate overlap (right panel) of previously documented diurnal locations of cranes (left panel; black areas indicate crane observations and boundaries are counties) with CDFW Central Valley Midwinter Waterfowl Survey transects (center panel; straight lines represent transect areas and boundaries are CVJV basins and sub-basins) in Central and Northern California.

Roosting Habitat and Requirements and Scenarios: We considered crane roost needs in terms of quality and extent sing the land cover map described in Section 4 of this report. Briefly, satellite-based land classification data, data on parcel boundaries, and prior wetland spatial layers were amalgamated to produce the map, identifying wetlands, agriculture, and other land uses in the Central Valley. The winters of 2020-2021 (wet), 2021-2022 (dry), 2022-2023 (dry, then wet), 2023-2024 (wet), and a simulated dry 2022-2023 (all dry—no late winter rains) acted as five landscape scenarios with which to understand water and land cover changes under different climactic conditions.

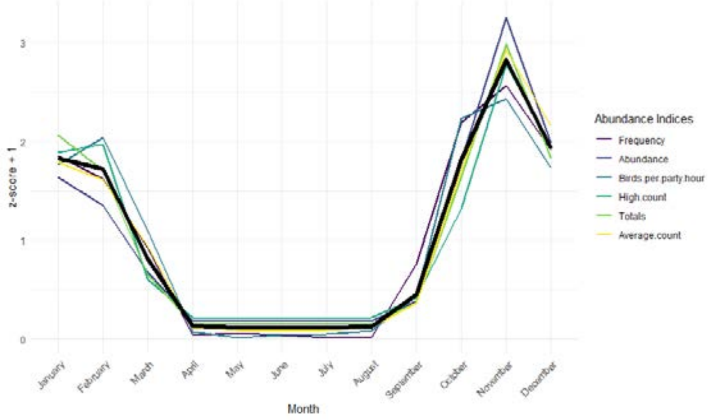

Figure 5.4.2: Normalized eBird indices of Sandhill Crane abundance in the Sacramento Valley and Yolo-Delta Regions. The bold black line is the average of the indices.

For each landscape scenario, we selected parcels that would provide habitat appropriate for crane roosting such that: (1) Land cover was either wetland or agriculture, which are well-documented roosting habitats, (2) The extent of flooding on a parcel was at least 5 hectares (12.36 acres), identified as a minimum size for roosting fields by Ivey et al. (2014), and (3) The average roost suitability score of pixels within the parcel was at least 0.108, which is 1 standard deviation below the mean roost score based on the Veloz et al. (2017) roost suitability model (detailed below).

Under each scenario, we calculated how many cranes could be accommodated by flooded wetlands and flooded agriculture, including rice. Ivey et al. (2014) found that crane roosting density during this Oct-Feb period did not vary significantly with parcel size, averaging 1.0 birds per hectare (0.40 birds/acre) in wetlands and 1.9 birds per hectare (0.77 birds/acre) in agriculture in the Yolo-Delta Region. We refer to these habitat-specific values as "recommended roost densities" and used them to determine roost extent, though the authors recommended managing for a single, intermediate roost density (1.5 birds per hectare) for simplicity. While roosting densities orders of magnitude higher have been observed in some circumstance (e.g., >100 cranes per hectare at mid-continent staging grounds; Krapu et al. 1984) we did not explore implications of allowing for denser roosts.

We estimated the number of cranes to be supported by determining the ratio of the January midwinter survey count to the eBird composite abundance for January, then applying that ratio to other months Oct-Feb and adding any additional growth specified in population objectives Overall values were obtained by averaging across months. To determine habitat adequacy in each of the five scenarios, we calculated the amount of habitat provided by wetlands, non-rice agriculture, and rice farms each month at the literature-based roosting densities. Though birds are often site-faithful, we did not require that the same parcels be flooded throughout the non-breeding period. Any deficit in roosting habitat was converted to acres of additional flooded rice needed.

Optimal Crane Roosting Locations: To prioritize areas where rice could best serve roosting needs, we relied on a major prior mapping and modelling effort by Veloz et al. (2017). The authors used roost location data from Ivey et al. (2016a) and The Nature Conservancy along with environmental data (land cover type, flooding extent, climate) within 5 km of each raster pixel to determine which environmental factors corresponded with roosting locations. Averaging yearly maps based on a decade of roosting locations yielded an overall roost suitability map. In tests of the map's ability to predict future roosts (see Appendix A.4), roost sites used to create the map averaged a suitability score of 0.36 (95% CI: 0.33 – 0.39), post-2017 roosts not used to create the map averaged 0.26 (95% CI: 0.20 – 0.31), and pixels chosen at random averaged 0.04 (95% CI: 0.037 0.048). Thus, we confirmed that actual roosts were highly ranked by the model. For each parcel identified as growing rice in at least one year of the scenarios, we averaged the pixels falling within the parcel for an overall roost suitability score. We then selected parcels in order of high suitability scores until the target acreage was met.

5.4.3 Results

Based on five years of aerial surveys in January, a mean of 38,887 Sandhill Cranes (95% CI: 33,757 – 44,797) used the surveyed portions of California's Central Valley each year. An average of 27.9% (range: 20.2% - 33.9%) of these Central Valley observations were in the Sacramento Valley, and an average of 65.2% (range: 57.8% - 75.1%) were in the Yolo-Delta Region, with the remainder of observations in the San Joaquin and Tulare Regions (Table 5.4.1).

Our literature review of Sandhill Crane conservation goals yielded quantitative population objectives. Reports by the Pacific Flyway Council (PFC) reiterated a 1983 objective of maintaining 20,000-25,000 cranes in the Lesser-dominated Pacific Coast population (PFC 2020) and at least 7,500 cranes for the Greater-dominated Central Valley population (PFC 1997). Assuming all cranes from these populations are in the Central Valley for winter, this is an overall objective of 27,500-32,500 cranes of these winter-sympatric, mixed subspecies populations. No specific population objective is presented in the 2020 Central Valley Joint Venture (CVJV) Implementation Plan, one of the primary planning documents for avian conservation in the region. However, Shuford and Dybala (2017) presented objectives that were more related to CVJV efforts. The authors recommended a doubling of the current wintering crane population (not distinguished between Pacific Flyway and

Central Valley populations, nor between subspecies) over the next 100 years. This objective was also presented in terms of shorter-term increases of 10% per decade. Since the PFC objectives have been met based on midwinter survey data, we followed the Shuford and Dybala (2017) objective of a 10% increase of wintering CV cranes for remaining calculations. We determined a target population of 47,181 (95% CI: 40,957 – 54,352) for the Central Valley, which is the average population of cranes in the Central Valley Oct-Feb, plus 10%. Assuming that current regional proportions hold, this amounts to a target of 43,705 in the combined Sacramento Valley and Yolo-Delta (13,459 cranes in the former, 30,246 in the latter).

Table 5.4.1. CDFW Central Valley Midwinter Waterfowl Survey estimates of Sandhill Crane abundance and population objectives.

January of	**Estimated January population,** **Sacramento Valley**	**Estimated January population,** **Yolo-Delta**	**Estimated January population,** **Central Valley-wide**
2016	7,799	27,439	38,606
2017	14,372	26,988	44,005
2018	13,175	25,836	44,695
2020	14,185	25,330	41,788
2023	5,933	19,051	25,342
Mean January Population *(95% CI)*	**11,093** *(8,524 – 14,436)*	**24,929** *(22,337 – 27,821)*	**38,887** *(33,757 – 44,797)*
Pacific Flyway Council Population Objective (combined Central Valley and Pacific Flyway populations)			**27,500-32,500**
Next-Decade Population Objective, Yolo-Delta + Sacramento Valley (mean Oct-Feb population in these regions + 10%)			**43,705**

Roosting Habitat and Requirements and Scenarios: In all five habitat scenarios, the amount of flooded habitat provided by a combination of wetlands, non-rice agriculture, and rice was sufficient to accommodate recommended roost densities of the estimated target crane populations from Nov-Feb (Figure 5.4.3). However, in all but one scenario (2020-2021; wet), there was a deficit of roosting habitat in October, such that an additional mean of 26,059 (S.D. = 3,804) acres of flooded rice would be required to support optimal roost densities; otherwise, roosts would have to be occupied more densely, birds would have to move elsewhere, or other changes might occur. Overall, flooded rice was most critically needed in October and November to complement flooded non-rice agriculture and flooded wetlands, typically 33,019 acres in October and 43,139 acres in November (Table 2). This peak need relates to crane numbers peaking in November (Figure 2) while flooding typically peaks later in the water year (Figure 3). The amount of flooded rice potentially used/needed is lower Dec-Feb (Table 5.4.2).

Optimal Crane Roosting Locations: We mapped the average amount of flooded rice required at the most severe "pinch point" during November. The Yolo-Delta Region had hotspots of high crane roost suitability (Veloz et al. 2017) such that 68.9% of the highest-rated potential roost fields were from this region red parcels in Figures 4 and 5), despite its much lower levels of rice cultivation relative to the Sacramento Valley Region. Overall, crane roosts were prioritized for the Yolo-Delta Region, southeast of Willows, and West of Live Oak.

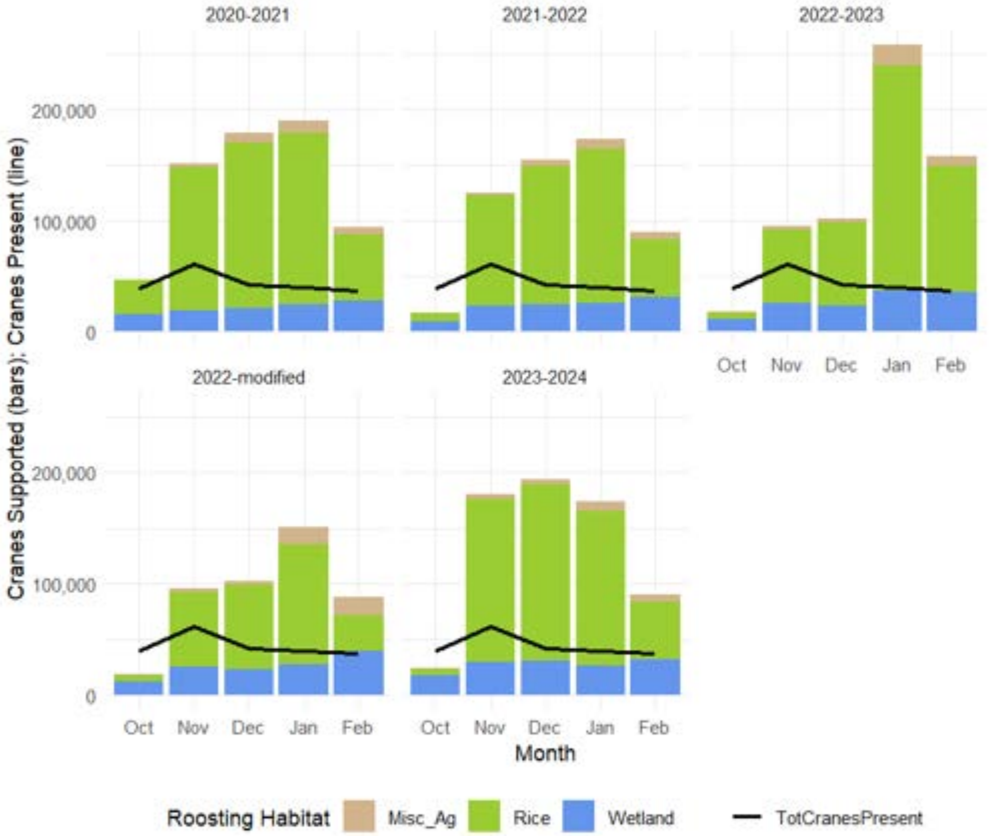

Figure 5.4.3. Roosting habitat availability (stacked bars) in terms of number of cranes supported at recommended densities, and roosting habitat need (black line) to support target numbers of cranes in the Sacramento Valley and Yolo-Delta Regions.

Table 5.4.2. Acres of flooded rice needed to complement flooded wetlands and flooded non-rice agriculture to support cranes at recommended densities. This includes rice that was flooded under the scenarios as well as any additional flooded rice needed to make up for overall roost habitat deficits.

Scenario	Oct	Nov	Dec	Jan	Feb
2020-2021	30,403	50,443	16,037	4,788	3,884
2021-2022	38,748	45,635	15,571	6,908	0
2022-2023	34,540	42,253	19,821	0	0
2023-2024	26,865	35,111	8,790	7,001	0
2022-modified	34,540	42,253	19,821	0	0
Mean	33,019	43,139	16,008	3,740	777

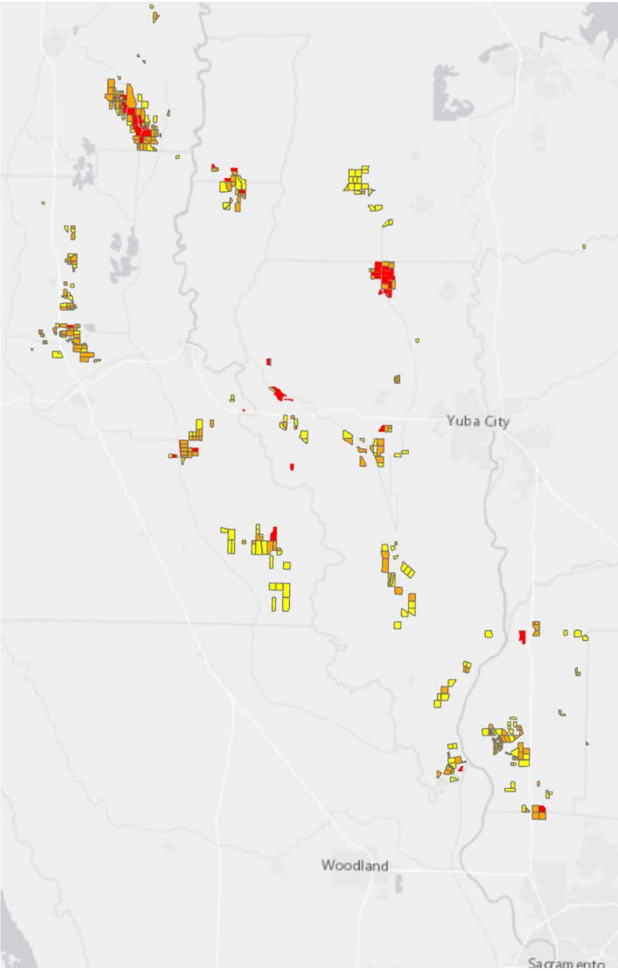

Figure 5.4.4: Sacramento Valley portion of map of optimal rice fields (red = highest third of suitability; yellow = lowest third of suitability) to support crane roosting. Fields were planted in rice at least once over the past four years. Approximately 43,139 acres of fields, the minimum recommended footprint of flooded rice, are shown collectively between Figures 4 and 5.

5.4.4 Key findings and priorities:

- The Yolo-Delta region supports more wintering Sandhill Cranes than the Sacramento Valley, at least in January, and it is a hotspot of high-suitability roost habitat. Therefore, it may be especially important to maintain rice cultivation in this region.
- October and November are key months for supplying flooded roosting habitat, because crane abundance peaks in November, but flooded potential roost habitat is typically not at its maximum extent until later in winter. Balancing unflooded food supply with adequate roost locations will be important to support the habitat complex conservation strategy.
- Flooded wetland habitat alone is almost always insufficient to support crane roosts at recommended densities.
- Based on the literature, shallow flooding is predicted to be the most beneficial management practice, because cranes often roost at shallower depths (10 cm or 15.5 cm average depths, depending on the study), and very shallowly flooded fields may support foraging as well.

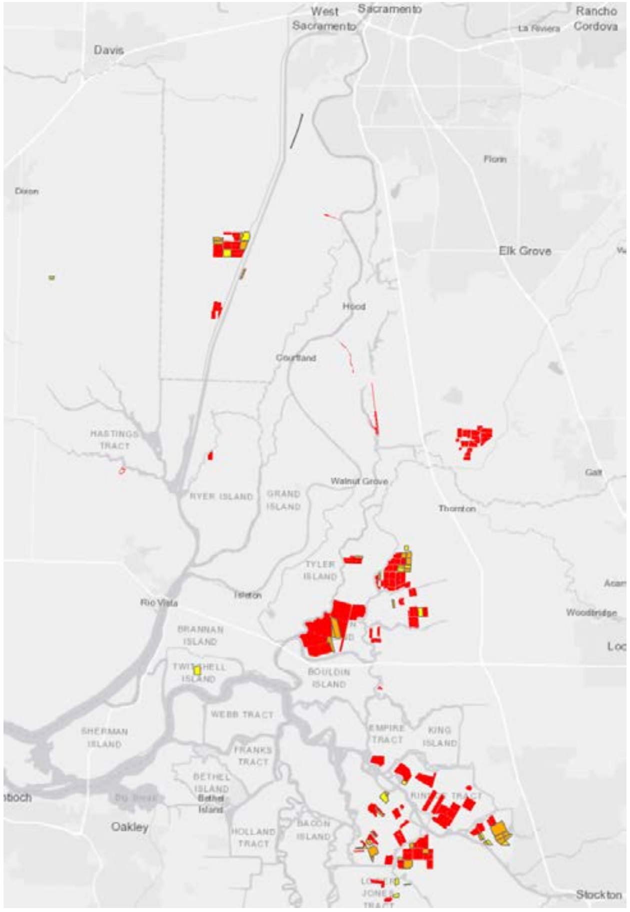

Fig. 5.4.5: Yolo-Delta portion of map of optimal rice fields (red = highest third of suitability; yellow = lowest third of suitability) to support crane roosting. Fields were planted in rice at least once over the past four years. Approximately 43,139 acres of fields, the minimum recommended footprint of flooded rice, are shown collectively between Figures 5.4.4 and 5.4.5.

- Though rice has not been identified as a primary food source for Sandhill Crane as often as other grains (more usually corn or wheat; Gerber et al., 2020), examining the use of rice as foraging habitat in future analyses could provide a fuller picture of rice dependence.

- Rice is a unique conservation opportunity for cranes because it can serve as both roosting and foraging habitat, depending on management practices.

5.4.5 References

Ballard, B. M., and J. E. Thompson. 2000. Winter diets of sandhill cranes from central and coastal Texas. *The Wilson Bulletin* **112:** 263-268.

Boggie, M. A., D. P. Collins, and S. A. Carleton. 2023. Availability of supplemental corn for sandhill cranes, light geese, and dabbling ducks wintering in New Mexico. *Journal of Fish and Wildlife Management* **14:** 51-61.

Bonat, W. H., B. Jørgensen, C. C. Kokonendji, J. Hinde, and C. G. Demétrio. 2018. Extended Poisson–Tweedie: properties and regression models for count data. *Statistical Modelling* **18:** 24-49.

Central Valley Joint Venture (CVJV). 2020. Central Valley Joint Venture 2020 Implementation Plan. U.S. Fish and Wildlife Service, Sacramento, California, USA.

Collins, D. P., M. A. Boggie, K. L. Kruse, C. M. Conring, J. P. Donnelly, W. C. Conway, and B. A. Grisham. 2023. Roost sites influence habitat selection of sandhill cranes (*Antigone canadensis tabida*) in Arizona and California. *Waterbirds* **45:** 428-439.

Donnelly, J. P., S. L. King, J. Knetter, J. H. Gammonley, V. J. Dreitz, B. A. Grisham, M. C. Nowak, and D. P. Collins. 2021. Migration efficiency sustains connectivity across agroecological networks supporting sandhill crane migration. *Ecosphere* **12:** e03543.

Gerber, B. D., J. F. Dwyer, S. A. Nesbitt, R. C. Drewien, C. D. Littlefield, T. C. Tacha, and P. A. Vohs. 2020. Sandhill crane (*Antigone canadensis*), version 1.0. In *Birds of the World* (A. F. Poole, editor). Cornell Lab of Ornithology, Ithaca, New York, USA.

Ivey, G. L., B. D. Dugger, C. P. Herziger, M. L. Casazza, and J. P. Fleskes. 2014. Characteristics of sandhill crane roosts in the Sacramento-San Joaquin Delta of California. *Proceedings of the North American Crane Workshop* **13:** 12-19.

Ivey, G. L., B. D. Dugger, C. P. Herziger, M. L. Casazza, and J. P. Fleskes. 2015. Wintering ecology of sympatric subspecies of sandhill crane: correlations between body size, site fidelity, and movement patterns. *The Condor: Ornithological Applications* **117:** 518-529.

Ivey, G. L., C. P. Herziger, D. A. Hardt, and G. H. Golet. 2016a. Historic and recent winter sandhill crane distribution in California. *Proceedings of the North American Crane Workshop* **13:** 54-66.

Krapu, G.L., Facey, D.E., Fritzell, E.K. and Johnson, D.H., 1984. Habitat use by migrant sandhill cranes in Nebraska. The Journal of wildlife management: 407-417.

Lewis, J. C. 1974. Ecology of the sandhill cranes in the southeastern Central Flyway. Dissertation. Oklahoma State University, Stillwater, Oklahoma, USA.

Littlefield, C. D. 2002. Winter foraging habitat of greater sandhill cranes in northern California. *Western Birds* **33:** 51-60.

Littlefield, C. D., and S. P. Thompson. 1982. The Pacific Coast population of lesser sandhill cranes in the contiguous United States. Pages 288-294 in J. C. Lewis, editor. *Proceedings of the 1981 International Crane Workshop*. National Audubon Society, Tavernier, Florida, USA.

Pearse, A. T., G. L. Krapu, D. A. Brandt, and P. J. Kinzel. 2010. Changes in agriculture and abundance of snow geese affect carrying capacity of sandhill cranes in Nebraska. *The Journal of Wildlife Management* **74:** 479-488.

Pogson, T. H., and S. M. Lindstedt. 1991. Distribution and abundance of large sandhill cranes, *Grus canadensis*, wintering in California's Central Valley. *The Condor* 93:266-278.

Pacific Flyway Council (PFC). 1997. Pacific Flyway management plan for the Central Valley Population of Greater Sandhill Cranes. Pacific Flyway Study Committee, care of U.S. Fish and Wildlife Service, Portland, Oregon, USA. Unpublished report.

Pacific Flyway Council. 2020. Status review for the Pacific Coast Population of Sandhill Cranes. Pacific Flyway Council, care of U.S. Fish and Wildlife Service, Division of Migratory Bird Management, Vancouver, Washington, USA.

Shaskey, L. 2012. Local and landscape influences on sandhill crane habitat suitability in the northern Sacramento Valley, California. Dissertation. Sonoma State University, Sonoma, California, USA.

Shuford, W.D., Reiter, M.E., Sesser, K.A., Hickey, C.M. and Golet, G.H., 2019. The relative importance of agricultural and wetland habitats to waterbirds in the Sacramento–San Joaquin River Delta of California. *San Francisco Estuary and Watershed Science*, **17: 1-25**.

Veloz, S.D., Salas, L., Elliott, N., Jongsomjit, D., Shuford, W.D., 2017. Conservation reserve planning for wintering Sandhill cranes in the Central Valley of California: Report to the Nature Conservancy. Point Blue Conservation Science, Petaluma, CA.

5.5 A Conservation Footprint in California’s Rice Fields to Enhance Native Fish Conservation

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Highlights

- Native fishes, including salmon, are collapsing in the Sacramento Valley.
- Current and past research highlights the potential of winter-flooded rice fields to serve as fish habitat, especially in the Sutter and Yolo Bypasses.
- Results from a population model, developed exclusively for this report, show that full-scale implementation of bypass rice field management could nearly double salmon cohort replacement rates (CRR), but this boost still falls short of what is needed for full population recovery.
- Fish food, grown on 'dry-side' rice fields is a promising complementary practice, currently led by California Trout Inc. This practice could further increase cohort replacement rates.
- Key challenges for the future include the inherent dispersal limitations of fishes, needs for additional research, regulatory constraints as fish populations further decline, and various other implementation issues.

5.5.1 Background and context

87% of California’s native fish populations are under severe decline and face extinction if present trends continue (Moyle et al. 2011; Rypel and Moyle 2024). Shockingly, these trends are independent of effects of climate change, which only worsens the prognosis (Moyle et al. 2017). Central Valley fishes are particularly threatened, not only from severe fragmentation by dams (Yoshiyama et al. 1998; Lindley et al. 2006), but also through loss of wetlands (Moyle 1995). California’s floodplain wetlands are now some of the most converted and imperiled ecosystems in the world (Opperman 2012; Mount et al. 2023). Over a short period of time, humans eliminated 95% of the Central Valley floodplains that historically supported native fishes (Frayer et al. 1989; Sommer et al. 2003). Negative trends are only intensifying, and as of the writing of this report, multiple runs of Chinook salmon in California are collapsing in real-time.

There is increasing research interest in understanding how to use winter-flooded rice fields to support native California fishes, especially salmon (Sommer et al. 2001; Rossi et al. 2024). Much of this work focuses on naturally-flooded rice fields on the unprotected side of levees, especially in the Yolo and Sutter Bypasses (but see ‘fish food’ section below). Sommer et al. 2001 and Katz et al. 2017 demonstrated rigorous growth of wild- and hatchery-derived juvenile Chinook salmon grown in Yolo Bypass rice fields, approaching growth rates of 1 mm/d in fork length. These results were replicated by Jeffres et al. 2020, Sommer et al. 2020, Holmes et al. 2021, Tallman 2024, Tallman et al. 2025, and others (e.g., Wampler unpublished). Further, growth is positively associated with flood duration in California agricultural floodplains (Takata et al. 2017). Rapid growth is driven by massive concentrations of zooplankton (e.g., 53x higher than river channel) that quickly develop in rice fields upon flooding, especially during dry years (Goertler et al. 2018; Jeffres et al. 2020). Variations in assembly dynamics of the zooplankton food are influenced by water residence time (Corline et al.

2021), and water source (well versus surface), which are largely managed features of rice landscapes.

A large battery of experiments was conducted by researchers at UC Davis during 2019-2023 studying how to develop a USDA NRCS practice standard for rearing river-origin salmon on naturally-flooded rice fields. Tallman (2024) inserted coded wire tags in 30,000 Chinook salmon fry released at Conaway Ranch during early winter 2019. Estimates of the smolt-to-adult return rate for these fish over the following years was higher than most other management actions taken that year. During winter 2020, Tallman (2024) tested in-field growth and survival of 10,000 Chinook salmon stocked into 8 replicated fields prepared in different ways (adding ditches, adding coarse woody debris, adding ditches and coarse woody debris, and controls). These experiments showed none of the field preparation techniques resulted in higher growth or survivorship compared to controls, both of which were high across all treatments. These results support earlier experiments by Corline et al. 2017 and Holmes et al. 2021. Regarding outmigration survival, most telemetry studies found either improved survival of floodplain-reared salmon relative to controls or no difference (Johnston et al. 2018; Tallman 2024; Wampler unpublished). One acoustic telemetry experiment showed that a batch of floodplain-reared fish at Conaway Ranch had poor outmigration survivorship through the Yolo Bypass (essentially 0%), but these fish were released late in the spring (May). Thus, the Yolo Bypass appears to be excellent salmon habitat early in the season, but not late.

Overall, salmon studies supported a draft NRCS practice standard that is relatively simple. It is necessarily a flood extension practice, meaning boards are used to extend the hydroperiod, grow zooplankton, and contain fishes but with an option for volitional passage. Without boards, fields would rapidly drain and the hydroperiod would be very short. Field preparation can be minimal but does require some straw to prevent decomposition-related dissolved oxygen problems. Flooding depth is recommended at 10-12 inches (305 mm), with deeper depths preferred to minimize predation of fishes by wading birds. In bypasses, upon natural flood events, growers wait until containment of rice checks and subsequently install modified boards containing a hole and notch for volitional passage of fishes, especially juvenile salmonids. Water is then held and managed by the grower until March 1, or a time at which temperature and/or oxygen conditions erode to a threshold point, at which time boards are pulled and water and fish evacuated.

During winter 2022, natural flooding from the Sacramento River allowed a significant assessment of the degree to which wild and in-river fish are entrained into these habitats upon floods. Using genetics, all four runs of Chinook salmon, plus steelhead, as well as a diversity of other native fishes were entrained into and utilized the field (Fig. 5.5.1). Some nonnative species were also present. Acoustic telemetry work on outmigrants from the rice field showed that fish reared in these habitats appear to sometimes have an outmigration survival advantage, both through the Sutter Bypass, as well as, out to the ocean. At other times, the effect of rice rearing is neutral (there is no benefit, but it is also not harmful).

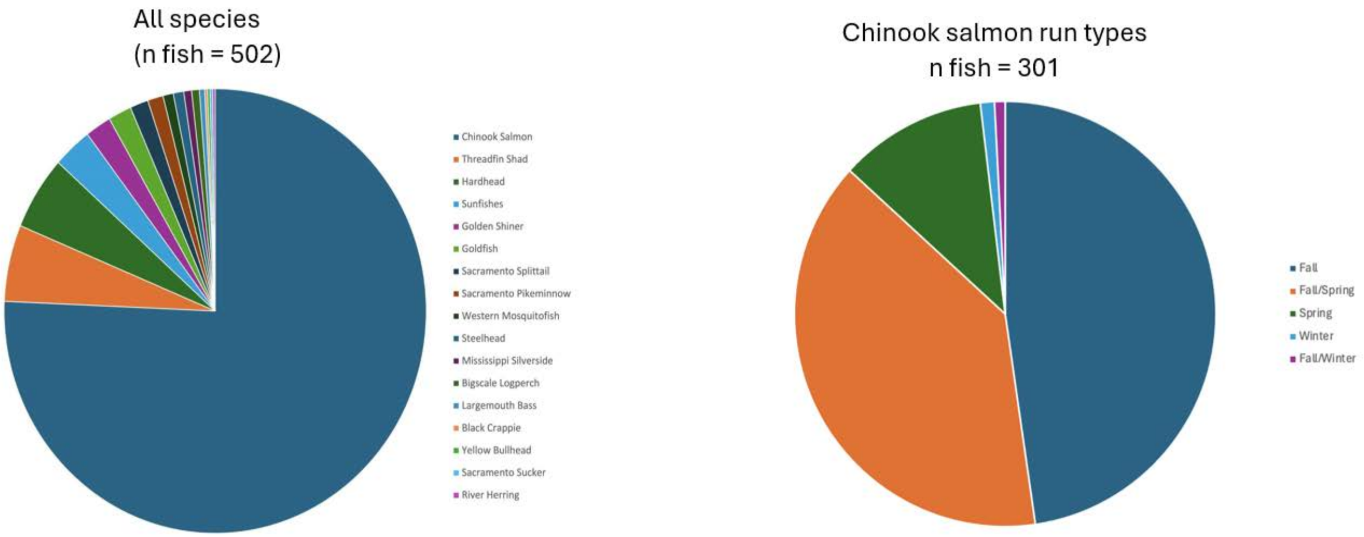

Figure 5.5.1: Catch of fishes from a fyke operated daily on a naturally flooded rice field in the Sutter Bypass, winter 2022-2023. Salmon run types were identified using genetic clips and analyzing them for the GREB1L/ROCK1 region. Data from Aronson et al. 2024.

5.5.2 Methods

In this report, we present for the first time a conceptual life-cycle model for fall-run Chinook salmon to test the degree to which salmon populations are boosted by floodplain management. The model integrates information on four major sources of salmon utilizing rice fields - Sacramento River, Sacramento River Tributaries, Yuba River, and Feather River. For each of these systems, the model ingests information on all facets of the salmon life-cycle, including egg incubation and juvenile survival in tributary, mainstem and off-channel habitats. The model also includes an ocean stage component, yielding escapement, return of spawning adult adults, and an egg incubation phase. The model builds directly from previously published California salmon population models (Bellido-Leiva et al. 2021; Bellido-Leiva et al. 2022) and can be used to simulate management scenarios of interest.

In this study, the two primary factors driving model results are a) the floodplain hydroperiod (rearing time); and b) % in-river salmon entrained into floodplains. For our management scenario we use a middle-of-the-road scenario (50 day hydroperiod) which we believe will be common in the future with the opening of the Yolo Bypass notch combined with the draft NRCS practice standard method. We also use an estimate of 35% entrainment into the bypass under notch management as a starting point. Our model was built using Python recursive coding software, and simulations were run for a total of 20,000 cohorts for each source population and scenario.

We express results of population modeling using cohort replacement rate (CRR). CRR is mathematically the boundary between ocean stage survival and freshwater stage survival of salmon. When populations exceed the CRR threshold, it means populations are fully replacing themselves; thus, populations should be stable or increasing. Yet when populations dip below the CRR threshold, it means populations are predicted to decline. Because of the ocean survival function used, which is agnostic to ocean conditions, increased ocean survival in the model is primarily a function of fork length; thus, factors in the scenario modeling that boost fork length also increase CRR.

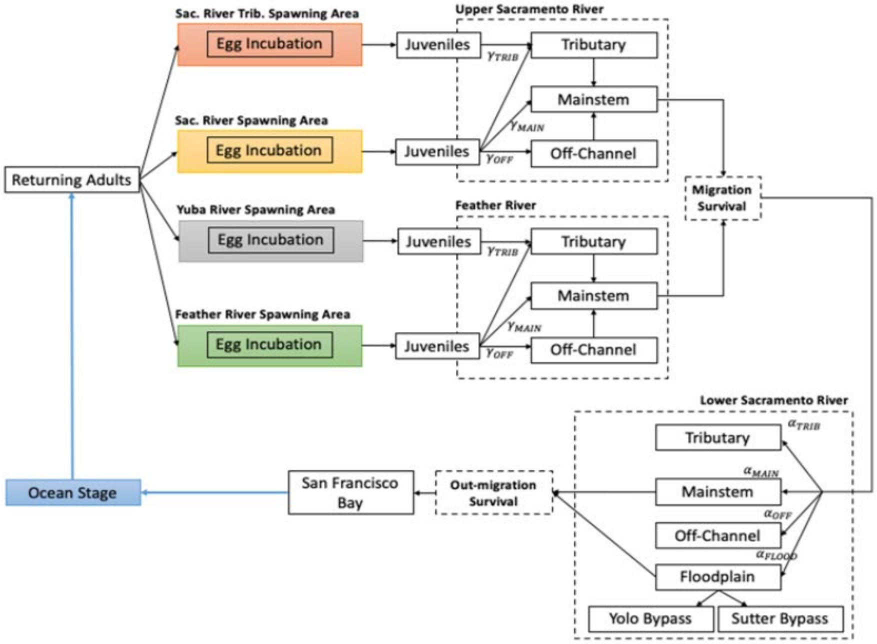

Figure 5.5.2: Conceptual life-cycle model for fall-run Chinook salmon.

5.5.3 Results

For the four focal source populations (Sacramento River, Sacramento River Tributaries, Feather River, and Yuba River), % samples with CRR exceeding the threshold were just 17%, 19%, 20%, and 30%, respectively under a business-as-usual scenario (Fig. 2). The mean % over threshold samples are just 22%. Therefore, it is unsurprising that Central Valley fall-run Chinook salmon are currently declining so strongly. By simulating implementation of all acres of bypass fields into full practice standard management, our model projects that percentages of over threshold samples jump substantially. The % samples with CRR exceeding the threshold increases to 25%, 32%, 34%, and 59% for the same four source populations, respectively (Fig. 2). Thus, mean % over threshold samples increase to 38% overall under a full floodplain management scenario. Therefore, CCR projects to nearly double with full practice standard implementation. However, it is notable that this increase, while substantive, is not near enough on its own to approach 100% (full replacement).

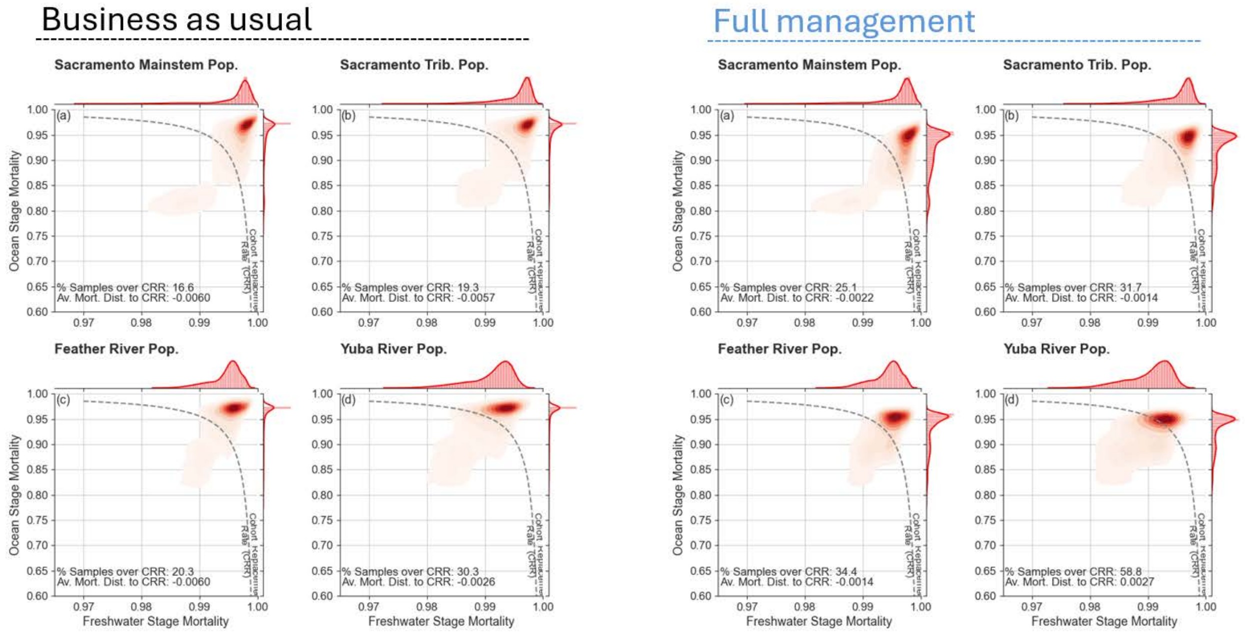

Figure 5.5.3: Results of population models for four focal source populations of Chinook salmon population comparing a business-as-usual scenario with full-scale management like that outlined in the draft NRCS practice standard.

There are two major implications from these findings. First, every acre of bypass fields enrolled in the practice standard is needed to maximally boost salmon populations. The footprint of bypass rice fields needed for salmon, is quite simply, all of it. Additional naturally-flooded acres would only boost this number more, but there are not enough bypass rice acres to approach full replacement. Bypass fields are used by juveniles of all four salmon runs and myriad other native fishes such as steelhead, splittail, hardhead, Sacramento pikeminnow and Sacramento sucker (Fig. 1). These findings are also consistent with those of related studies (Feyrer et al. 2006; Sommer et al. 2008; Sommer et al. 2014). Consequently, the second implication of this study is that other management actions are needed to further boost salmon populations. For example, increased flows (Michel et al. 2021; Jacinto et al. 2023), improved fish passage including dam removal (Börk and Rypel 2021; Pess et al. 2024), growing 'fish food' (see section 5.5.4), and other habitat actions like temperature management (Beechie et al. 2013) and spawning habitat rehabilitation (Zeug et al. 2013) are also important for increasing CRR across the Sacramento system. Combined these actions can serve as a constellation of strategies for managing salmon for resilience under a fast-changing environment (Herbold et al. 2018).

5.5.4 Rice as a source of 'fish food'

Here, we touch on one particularly promising and germane idea for the rice footprint - the "fish food" strategy (Jeffres et al. 2017; California Trout 2018, 2019). This practice entails winter wetting of rice fields to stimulate zooplankton production, followed by strategic draining of food at key times (*e.g.,* when salmon are migrating in the vicinity of fish food fields/discharges). There is strong evidence that floodplains comprised of rice fields export prey to downstream habitats upon floods (Sturrock et al. 2022). Not only can the food get successfully into the river, but in-river fish access these resources in support of growth, at least for experimentally-caged fish (California Trout 2018, 2019). The net result of the potential fish food practice is therefore additional growth and size of out-migrating juveniles, ultimately leading to a likely benefit (reduction) in freshwater and ocean mortality as described by the model above. California Trout Inc is leading the development and implementation of this practice. As of water year 2024, a total of 29,400 acres were enrolled in the practice (Figure 5.5.4), but because this practice involved 'double cropping' (i.e., growing then draining, followed by another cycle of growing and draining during the same winter), the equivalent net acreage effect was 54,800 acre-cyles. For 2025, Caltrout has contracted for 59,600 acre-cycles on 25,100 acres. The fish food concept is also important to consider on natural and restored wetlands, in addition to just rice fields.

Future modeling akin to that presented above can also quantify the benefit of the fish food practice to CRR. However, there remain some uncertainties that currently limit such an effort. The productivity of different rice fields is spatiotemporally heterogeneous (Cordoleoni et al. 2022) but may be influenced directly by how fields are managed in terms of water source, soil, and straw decomposition. Furthermore, the half-life of different food sources, while largely unknown, is managed through CalTrout's distance selection criteria. This decision selection criteria can ultimately be incorporated into a potential fish food population model.

Nonetheless, if we assume just a 10% (conservative) efficacy of the fish food practice relative to the bypass practice, this would result in a net effect of +0.000126% CRR per acre. However, there are considerably more dry side acres in the Sacramento Valley. Therefore, even with a much-reduced efficacy, 54,000 acres of fish food fields (as currently enrolled) is projected to deliver an additional 6.8% CRR. Yet if efficacy is more like 50%, the CRT boost from fish food jumps to 34%, with no increase in enrolled acreage. These numbers increase substantially as enrolled acreage ramps towards 200,000-300,000 acres. Future research quantifying the impact of the fish food practice on CRR will therefore be quite useful. Both the bypass and fish food practices are highly complementary with one another; thus, a next generation life-cycle model that evaluates the population effect of both practices will ultimately be key to articulating management goals.

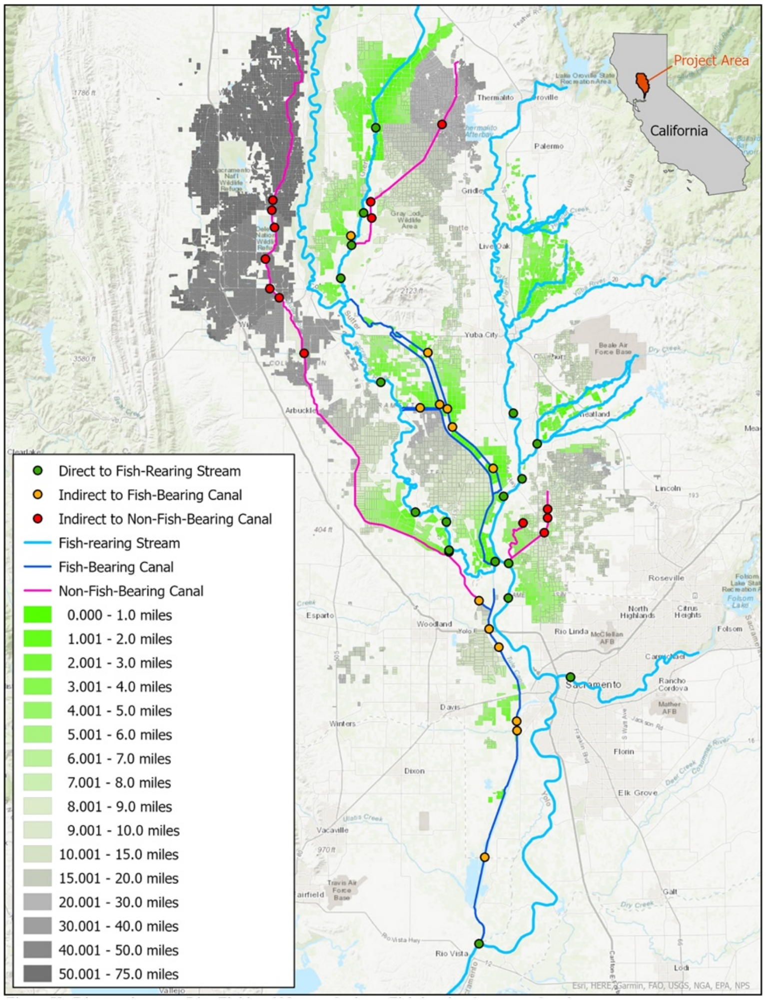

Figure 5.5.4. Preliminary estimated distances between rice fields and their nearest outlet to a fish-bearing stream or canal. Colors are graduated based on distance in miles, from green (close) to grey (far). Important note: these data are preliminary. More detailed information on local conditions and infrastructure needs to be incorporated. Spatial data developed and created by Skyler Lewis and Bethany Hackenjos (FlowWest 2023) with edits contributed by Jacob Montgomery (CalTrout) and Dan Fehringer (Ducks Unlimited). Map created by Dan Fehringer.

5.5.5 Constraints and future research

This work highlights key knowledge gaps that could improve management of the rice footprint for native fishes. This includes:

- *Quantifying % of in-river salmon entrained into floodplains*. Because % of entrained fish into bypasses drives population model results, higher fractions of entrained salmon will produce higher projected positive effects on salmon and vice versa. This recommendation is consistent with those of del Rosario et al. (2013) who found residency of winter-run Chinook salmon was high in the Yolo Bypass and that managers may need to consider ways of increasing rearing opportunities for fish within the Yolo Bypass and its rice footprint. Sommer et al. (2005) also noted extended rearing of hatchery-released juvenile fall-run

Chinook salmon on rice-rich regions of the Yolo Bypass. There are currently only poor estimates of % in-river fish entrained into floodplains, and they likely vary substantially from year-to-year depending on flow conditions. Along these same lines, the model presented in this report shows how management actions taken to increase this percentage are extremely likely to aid Central Valley Chinook salmon recovery overall. California managers already pursue actions to prevent salmon from taking outmigration routes that lead to high mortality (e.g., Georgiana Slough). However, the reverse may also be true, and water managers and engineers might consider multiple ways (beyond 'weir notching') of increasing access of salmon to floodplains. Improved monitoring tools such as stable isotopes in archival tissues can aid in execution of such actions (Bell-Tilcock et al. 2021a; Bell-Tilcock et. al. 2021b).

- *Bringing hatchery fish directly to the floodplains*. An alternative method of increasing the % of salmon in floodplains would be to bring them there manually, such as in a hatchery truck. While hatchery management certainly carries its own risks to native fishes, the potential of marrying hatchery releases with habitat access and rehabilitation remains high (Rypel and Moyle 2023). In the Central Valley, most in-river salmon are already of hatchery origin. Work from Tallman et al. (2025) shows that salmon can be safely reared on fish fields, including even those on the 'dry side' of the levee system. However, there has still never been a large (e.g., > 500,000 fish) release of salmon into a California rice field. A potential benefit from such releases could be that they can be more tightly controlled by managers, including potential pre-treatment for known issues, such as thiamine deficiency. Fish can also be released at smaller sizes (e.g., fry) which may aid in getting salmon to floodplain habitats faster and in accord with the natural flow regime of the Sacramento River. These releases can be considered as just one of many hatchery strategies taken to improve salmon fisheries. The efficacy of larger releases can be studied by scientists through various tagging technologies to understand effects of rearing strategy on outmigration survival and smolt-to-adult returns.
- *Efficacy of the fish food practice*. The behavior of salmon around fish food deliveries is somewhat unknown currently. While we are confident fish will locate food plumes and rear to take advantage of these resources, field research quantifying this effect for multiple runs is needed. Targeted acoustic telemetry studies, involving larger releases of tagged (likely hatchery) fish are needed. This information can be used to assess what % of fish rear in fish plumes, how long they rear, and what fraction are exposed to mortality though a potential 'dinner bell effect'. This information would provide the confidence needed to sufficiently estimate CRR benefits using our model or a similar one.
- *Dispersal limitations of fishes*. Relative to the other taxa presented in this report, fishes are much more dispersal limited. For example, wetland habitat once created, may quickly draw in birds from other regions and provide more rapid benefits to these wildlife. Birds are also inherently easier to count, and thus study. Fishes, because they require water and passage are much more difficult to count and manage. It is not enough to simply create the habitat, but we must also create, manage and monitor for safe, timely and effective passage.

- *Regulatory challenges*. Ironically, regulatory frameworks aimed at helping native fishes also threaten this work. There are currently so many listed fish species in the Sacramento River that regulatory hurdles and delays are a challenge to timely actions. As just one example, Central Valley spring-run Chinook salmon are crashing in their strongholds of Deer and Mill Creeks and are being considered for uplisting from 'threatened' to 'endangered' under the US Endangered Species Act. This variety of salmon is regularly captured on rice fields (Fig. 1), but under these circumstances, managers may be increasingly reluctant to pursue any action that involves 'take' of these fish, including scientific studies and management actions on rice. This hesitancy is certainly understandable but is likely a mistake. As model results demonstrate, floodplain access for salmon could substantially improve populations. The successful management models already developed for migratory waterfowl and shorebirds (as discussed in prior chapters) can continue to serve as guiding models for fishes. However, the regulatory challenges for fishes are unique, and the most complicated of all the taxa. For these reasons, future research and management of the California rice footprint requires serious collaborations across state and federal agencies, universities, landowners, NGOs and tribes.
- *Implementation hurdles*. Implementing the NRCS draft practice standard is important but may have a separate set of challenges. For example, activating all ~30k acres of bypass rice fields into the fish practice will require 100% uptake from the growers. Many growers will be enthusiastic about the practice, but others might be hesitant. In the end, making the practice attractively-funded for growers will be important to ensuring high uptake. As of writing this report, a total of $7M might be needed annually to fund the practice. Thus, funds from a combination of federal (e.g., NRCS) and other sources will be needed to create the pay incentive structures needed for implementation and high uptake. And even with attractive payments, growers may still have hesitations concerning the regulatory issues identified above, including liability fears regarding state- and federally-listed species.
- *Optimizing multiple practices*. California's agricultural floodplains have long been recognized as having potential for multi-sector socioecological compatibility (Sommer et al. 2001; Kamada et al. 2022). With the rise of multiple conservation practices for fishes and other taxa, there will be a need to make these practices as complimentary as possible to have the largest impact. Suddeth Grimm and Lund (2016) provide an example of how to develop a multi-objective optimization protocol to help planners identify the best management options with the least costs. Parts of this footprint report highlight some competing demands of the practices, including factors like water availability, depth of flooding, location and costs. A larger inter-taxa and intra-taxa (within just fishes) optimization model will likely be needed in the near future.

5.5.6 Conclusions

Fewer rice growers are interested in winter flooding. Reduced winter flooding for any reason functionally cuts the rice footprint available to help fishes. Innovative programs, such as NRCS payment structures, are needed to incentivize growers to continue cultivating rice, but in the most fish friendly ways. State and federal agencies must take action and find pathways to support these kinds of programs or risk losing the fish/rice footprint to other crops. The alternative crops are likely to provide little-to-no surrogate wetland benefits for fishes and for most other wetland-dependent taxa. Unless incentive programs are quickly adopted and stood up, prolonged droughts accelerated by climate change will increase water costs and ultimately promote loss and conversion of ricelands. All four Chinook salmon runs are collapsing in the Central Valley, and time is of the essence. Based on the available evidence, the rice footprint is not only likely essential for saving Central Valley Chinook salmon, but probably also many other native fishes.

5.5.7 References

Aronson, P. G., D. J. Alcott, C. A. Jeffres, D. E. Cocherll, N. A. Fangue, P. G. Buttner, and A. L. Rypel. 2024. Community assemblage of fishes on a seasonally-flooded rice field in northern California. American Fisheries Society, Annual Meeting, Honolulu HI USA.

Beechie, T., H. Imaki, J. Greene, A. Wade, H. Wu, G. Pess, P. Roni, J. Kimball, J. Stanford, and P. Kiffney. 2013. Restoring salmon habitat for a changing climate. River Research and Applications 29:939-960.

Bell-Tilcock, M., C. A. Jeffres, A. L. Rypel, M. Willmes, R. A. Armstrong, P. Holden, P. B. Moyle, N. A. Fangue, J. V. Katz, and T. R. Sommer. 2021. Biogeochemical processes create distinct isotopic fingerprints to track floodplain rearing of juvenile salmon. PloS ONE 16:e0257444.

Bell-Tilcock, M., C. A. Jeffres, A. L. Rypel, T. R. Sommer, J. V. Katz, G. Whitman, and R. C. Johnson. 2021. Advancing diet reconstruction in fisheye lenses. Methods in Ecology and Evolution 12:449-457.

Bellido-Leiva, F. J., R. A. Lusardi, and J. R. Lund. 2021. Modeling the effect of habitat availability and quality on endangered winter-run Chinook salmon (Oncorhynchus tshawytscha) production in the Sacramento Valley. Ecological Modelling 447:109511.

Bellido-Leiva, F. J., R. A. Lusardi, and J. R. Lund. 2022. Quantification of off-channel inundated habitat for Pacific Chinook salmon (Oncorhynchus tshawytscha) along the Sacramento River, California, using remote sensing imagery. Remote Sensing 14:1443.

Börk, K., and A. L. Rypel. 2019. Improving infrastructure for wildlife. Natural Resources & Environment 34:1-5.

California Trout Inc. 2018. Fish food on floodplain farm fields. Annual Report. California Trout Inc.

California Trout Inc. 2019. Fish food on floodplain farm fields. Annual Report. California Trout Inc.

Cordoleani, F., E. Holmes, M. Bell-Tilcock, R. C. Johnson, and C. Jeffres. 2022. Variability in foodscapes and fish growth across a habitat mosaic: Implications for management and ecosystem restoration. Ecological Indicators 136:108681.

Corline, N. J., R. A. Peek, J. Montgomery, J. V. E. Katz, and C. A. Jeffres. 2021. Understanding community assembly rules in managed floodplain food webs. Ecosphere 12:e03330.

Corline, N. J., T. Sommer, C. A. Jeffres, and J. Katz. 2017. Zooplankton ecology and trophic resources for rearing native fish on an agricultural floodplain in the Yolo Bypass California, USA. Wetlands Ecology and Management 25:533-545.

del Rosario, R. B., Y. J. Redler, K. Newman, P. L. Brandes, T. Sommer, K. Reece, and R. Vincik. 2013. Migration patterns of juvenile winter-run-sized Chinook Salmon (Oncorhynchus tshawytscha) through the Sacramento–San Joaquin Delta. San Francisco Estuary and Watershed Science 11.

Feyrer, F., T. Sommer, and W. Harrell. 2006. Importance of flood dynamics versus intrinsic physical habitat in structuring fish communities: evidence from two adjacent engineered floodplains on the Sacramento River, California. North American Journal of Fisheries Management 26:408-417.

Frayer, W. E., D. D. Peters, and H. R. Pywell. 1989. Wetlands of the California Central Valley: status and trends. U.S. Fish and Wildlife Service, Region 1, Technical Report.

Goertler, P., K. Jones, J. Cordell, B. Schreier, and T. Sommer. 2018. Effects of extreme hydrologic regimes on juvenile Chinook salmon prey resources and diet composition in a large river floodplain. Transactions of the American Fisheries Society 147:287-299.

Herbold, B., S. M. Carlson, R. Henery, R. C. Johnson, N. Mantua, M. McClure, P. B. Moyle, and T. Sommer. 2018. Managing for salmon resilience in California's variable and changing climate. San Francisco Estuary and Watershed Science 16.

Holmes, E. J., P. Saffarinia, A. L. Rypel, M. N. Bell-Tilcock, J. V. Katz, and C. A. Jeffres. 2021. Reconciling fish and farms: Methods for managing California rice fields as salmon habitat. PLoS ONE 16:e0237686.

Jacinto, E., N. A. Fangue, D. E. Cocherell, J. D. Kiernan, P. B. Moyle, and A. L. Rypel. 2023. Increasing stability of a native freshwater fish assemblage following flow rehabilitation. Ecological Applications 33:e2868.

Jeffres, C. A., E. J. Holmes, M. Ogaz, G. Saron, M. Tilcock, J. V. E. Katz, and J. Montgomery. 2017. Fish food on the floodplain farm fields: report of the 2017 pilot year investigations, Sacramento Valley. University of California Davis and California Trout Inc., Technical Report.

Jeffres, C. A., E. J. Holmes, T. R. Sommer, and J. V. Katz. 2020. Detrital food web contributes to aquatic ecosystem productivity and rapid salmon growth in a managed floodplain. PloS ONE 15:e0216019.

Johnston, M. E., A. E. Steel, M. Espe, T. Sommer, A. P. Klimley, P. Sandstrom, and D. Smith. 2018. Survival of juvenile Chinook salmon in the Yolo Bypass and the lower Sacramento River, California. San Francisco Estuary and Watershed Science 16.

Kamada, M., J. Nishihiro, and F. Nakamura. 2022. Governance for realizing multifunctional floodplain: flood control, agriculture, and biodiversity in yolo bypass wildlife area, California, USA. Pages 471-485 in F. Nakamura, editor. Green Infrastructure and Climate Change Adaptation: Function, Implementation and Governance. Springer Nature Singapore.

Katz, J. V. E., C. Jeffres, J. L. Conrad, T. R. Sommer, J. Martinez, S. Brumbaugh, N. Corline, and P. B. Moyle. 2017. Floodplain farm fields provide novel rearing habitat for Chinook salmon. PloS ONE 12:e0177409.

Lindley, S. T., R. S. Schick, A. Agrawal, M. Goslin, T. E. Pearson, E. Mora, J. J. Anderson, B. May, S. Greene, and C. Hanson. 2006. Historical population structure of Central Valley steelhead and its alteration by dams. San Francisco Estuary and Watershed Science 4.

Michel, C. J., J. J. Notch, F. Cordoleani, A. J. Ammann, and E. M. Danner. 2021. Nonlinear survival of imperiled fish informs managed flows in a highly modified river. Ecosphere 12:e03498.

Mount, J., P. B. Moyle, A. L. Rypel, and C. Jeffres. 2023. Nature's gift to nature in early winter storms. California WaterBlog, https://californiawaterblog.com/2023/01/15/natures-gift-to-nature-in-early-winter-storms/.

Moyle, P. B. 1995. Conservation of native freshwater fishes in the Mediterranean-type climate of California, USA: a review. Biological Conservation 72:271-279.

Moyle, P. B., J. V. Katz, and R. M. Quiñones. 2011. Rapid decline of California's native inland fishes: a status assessment. Biological Conservation 144:2414-2423.

Moyle, P. B., R. Lusardi, and P. Sameul. 2017. SOS II: fish in hot water. UC Davis Center for Watershed Sciences, CA USA.

Opperman, J. J. 2012. A conceptual model for floodplains in the Sacramento-San Joaquin Delta. San Francisco Estuary and Watershed Science 10.

Pess, G. R., M. L. McHenry, K. Denton, J. H. Anderson, M. C. Liermann, R. J. Peters, J. R. McMillan, S. J. Brenkman, T. R. Bennett, and J. J. Duda. 2024. Initial responses of Chinook salmon (Oncorhynchus tshawytscha) and steelhead (Oncorhynchus mykiss) to removal of two dams on the Elwha River, Washington State, USA. Frontiers in Ecology and Evolution 12:1241028.

Rossi, G. J., J. R. Bellmore, J. B. Armstrong, C. Jeffres, S. M. Naman, S. M. Carlson, T. E. Grantham, M. J. Kaylor, S. White, and J. Katz. 2024. Foodscapes for salmon and other mobile consumers in river networks. BioScience 74:586-600.

Rypel, A. L., and P. B. Moyle. 2023. Hatcheries alone cannot save species and fisheries. California WaterBlog, https://californiawaterblog.com/2023/04/30/hatcheries-alone-cannot-save-species-and-fisheries/.

Rypel, A. L., and P. B. Moyle. 2024. Watching native fishes vanish. California WaterBlog, https://californiawaterblog.com/2024/09/01/watching-native-fishes-vanish/.

Sommer, T., B. Harrell, M. Nobriga, R. Brown, P. Moyle, W. Kimmerer, and L. Schemel. 2001a. California's Yolo Bypass: Evidence that flood control can be compatible with fisheries, wetlands, wildlife, and agriculture. Fisheries 26:6-16.

Sommer, T., B. Schreier, J. L. Conrad, L. Takata, B. Serup, R. Titus, C. Jeffres, E. Holmes, and J. Katz. 2020. Farm to fish: lessons from a multi-year study on agricultural floodplain habitat. San Francisco Estuary and Watershed Science 18.

Sommer, T. R., M. L. Harrell, M. L. Nobringa, and R. Kurth. 2003. Floodplain as habitat for native fish: Lessons from California's Yolo Bypass. Pages 81-87 in P. M. Faber, editor. California riparian systems: Processes and floodplain management, ecology, and restoration. Riparian Habitat and Floodplains Conference Proceedings, Riparian Habitat Joint Venture, Sacramento, California.

Sommer, T. R., W. C. Harrell, and F. Feyrer. 2014. Large-bodied fish migration and residency in a flood basin of the Sacramento River, California, USA. Ecology of Freshwater Fish 23:414-423.

Sommer, T. R., W. C. Harrell, Z. Matica, and F. Feyrer. 2008. Habitat associations and behavior of adult and juvenile splittail (Cyprinidae: Pogonichthys macrolepidotus) in a managed seasonal floodplain wetland. San Francisco Estuary and Watershed Science 6.

Sommer, T. R., W. C. Harrell, and M. L. Nobriga. 2005. Habitat use and stranding risk of juvenile Chinook salmon on a seasonal floodplain. North American Journal of Fisheries Management 25:1493-1504.

Sommer, T. R., M. L. Nobriga, W. C. Harrell, W. Batham, and W. J. Kimmerer. 2001b. Floodplain rearing of juvenile Chinook salmon: evidence of enhanced growth and survival. Canadian Journal of Fisheries and Aquatic Sciences 58:325-333.

Sturrock, A. M., M. Ogaz, K. Neal, N. J. Corline, R. Peek, D. Myers, S. Schluep, M. Levinson, R. C. Johnson, and C. A. Jeffres. 2022. Floodplain trophic subsidies in a modified river network: managed foodscapes of the future? Landscape Ecology 37:2991-3009.

Suddeth Grimm, R., and J. R. Lund. 2016. Multi-purpose optimization for reconciliation ecology on an engineered floodplain: Yolo Bypass, California. San Francisco Estuary and Watershed Science 14.

Takata, L., T. R. Sommer, J. Louise Conrad, and B. M. Schreier. 2017. Rearing and migration of juvenile Chinook salmon (Oncorhynchus tshawytscha) in a large river floodplain. Environmental Biology of Fishes 100:1105-1120.

Tallman, R. L. 2024. Outmigration survival of juvenile Chinook salmon in reconciled ecosystems. Ph.D. Dissertation, University of California Davis, CA USA.

Tallman, R. L., A. N. Wampler, G. P. Singer, C. A. Jeffres, D. E. Cocherell, J. Colby, N. A. Fangue, R. A. Lusardi, and A. L. Rypel. 2025. Does method of field preparation affect survival and growth of juvenile Chinook salmon in agricultural floodplains? River Research and Applications:Published Online.

Yoshiyama, R. M., F. W. Fisher, and P. B. Moyle. 1998. Historical abundance and decline of chinook salmon in the Central Valley region of California. North American Journal of Fisheries Management 18:487-521.

Zeug, S. C., K. Sellheim, C. Watry, B. Rook, J. Hannon, J. Zimmerman, D. Cox, and J. Merz. 2014. Gravel augmentation increases spawning utilization by anadromous salmonids: a case study from California, USA. River Research and Applications 30:707-718.

6. Potential Economic Value of Riceland Habitats and Wildlife

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Highlights

- Section 5 documented the dependence of diverse species on rice farms as habitat, especially winter-flooded lands.
- Many detailed and elaborate econometric studies and simulations have projected household willingness to pay for contributions for better prospects for wildlife species, but no such studies have yet been devoted to rice and species listed. Nonetheless, the economic literature can contribute useful assessments indirectly.
- Data and methods from well-known publications and recent studies allow us to project alternative measures of the broadly perceived benefits of improved and expanded habitats for critical species.
- For example, a well-known study finds a species value of $28 per household. Applying that value to 13 million California households, adjusting for the contribution of rice acres to waterfowl diet and dividing by 400,000 acres of winter flooded rice yields a one-time value of about $550 per acre of rice.
- Such calculations must be developed and assessed with care because many estimates become too large to be plausible if many contributing households are included in the estimates.

6.1 Overview

By providing critical habitat, California rice provides important benefits to wildlife that are valued by people in California and beyond. As discussed, rice fields flooded during post-harvest periods provide food and habitat for waterfowl and shorebirds, the threatened Chinook Salmon, and giant garter snakes. In this section, we use data and methods from well-known publications and recent studies to project several alternative measures of the broadly perceived benefits of improved and expanded habitats for critical species. Specifically, we assess, and attempt to quantify using standard economic methods, the social welfare gains from improved wildlife habitat populations.

6.2 Willingness to pay for improved habitat for wildlife species

Given that no recent publications estimate the willingness to pay specifically for rice habitat for the species assessed in this report, we instead apply findings from species with similar characteristics for which agricultural lands provide habitat and to which crop practices contribute positively to species success. Such effects are typically categorized as public goods or positive externalities, and there are few market transactions from which one may measure monetary value directly. Instead, economics studies use estimates of preference from survey responses of consumers or those in the region or who may be familiar with the species. The data and approaches can be characterized as “contingent valuation” or “choice experiments” (Freeman et al, 2014).

Subroy et al (2019) conducted a meta-analysis regression on 109 willingness to pay (WTP) estimates for individual species, utilizing contingent valuation and choice experiment studies that reference a specific change in a single species population. They standardized each WTP estimate to a one-time, total WTP payment in 2016 US dollars. They found an average of $414 per affected household for an individual threatened species, with large variation depending on the type of species (mammal, bird, fish, etc.), the species' threat status, and whether a species was "charismatic" or not (Richardson & Loomis, 2009; Christie et al., 2006). The average WTP was estimated to be $572 per household for charismatic species compared to $106 per household for non-charismatic species. Accounting for inflation these estimates would be at least 25% larger in 2025 dollars.

Regional studies of relatively local habitat improvements include Lewis et al (2022), which used a choice experiment for the Oregon Coast Coho Salmon and found the marginal WTP to be between $0.08 and $0.18 per household for a one-year population increase of 1000 fish (roughly 0.67% of the baseline population). Haefele et al (2019) considered Northern Pintails and found a mean WTP of $28.46 per US household, $4.96 per Canadian Household, and $4.93 per Mexican household for the U.S. habitat. Assessing which households contribute to the WTP estimates determines the aggregate impacts. Applying a household WTP estimate to the 13 million households of California rather than the 130 million U.S. households would yield smaller estimates, but the important issue is for analysts to carefully match a sample estimate to the population from which the sample was drawn.

6.3 Willingness to pay associated with use values rather than simply existence values

About 89% of rice farmers and landowners allowed waterfowl hunting on their property, with 27% of the respondents collecting payment from hunting leases (Matthews, 2019). About 57% of respondents in the Pacific Flyway region mostly hunted on public lands or waters, while 15% hunted on private lands that required leases or permits. As one indicator of value about 80% of hunter survey respondents reported donating less than $250 to waterfowl conservation,15% donated between $250-$999, and 5% donated $1000 or more (Patton, 2018). For birdwatchers, 95% donated less than $250, 4% donated $250-$999, and 1% donated $1000 or more (Patton, 2021). Of course, even those benefiting often take advantage of the public good characteristics of habitat to avoid paying if they think their contribution will not affect their access.

WTP measures the perceived benefits of an additional "unit" of improvement for a certain species. The marginal cost measures the value of resource used additional to supply a "unit" of improvement. WTP values are likely to be relatively high for the first incremental improvements, while the marginal costs for those initial units are relatively low. The first added acres of habitat may contribute to the survival of the species and more acres would offer fewer perceived benefits than the previous ones. As more land is added, the farm practices needed likely become ever more costly. The complex balance between benefits and costs underlies choices of how much habitat is provided.

6.4 Illustrative valuation calculations for wildlife in California rice fields

To value the aggregate willingness to pay for species conservation, a policy-relevant calculation must consider the number of households to which the per-household payment applies and the period of time over which the payment applies. We used the 13 million California households for example calculations. Consider applying the estimate of $28.46 per household for Northern Pintails to waterfowl species using California rice fields. The result (13 million X $28.46) is a value of $369.98 million. Assuming rice comprises 60% of waterfowl food sources, rice fields contribute $221.99 million. Then, dividing $221.99 million by 400,000 rice acres yields $554.98 per acre permanent access to the rice fields.

Similarly, consider applying the estimate of $0.08 per household for an increase of 1000 fish per year to Chinook Salmon. A stocking density of 0.12 fish per m^2 is associated with a 61.6% survival rate; thus, one acre (4046 m2) of rice could support 485 fish, of which about 300 would survive. If 13 million households are willing to pay $0.08 for 1000 fish, we associate 300 fish with about $0.02 per household. Aggregated across the roughly 13 million households in California, this would be approximately $260,000 for just one acre compared to farmland prices of less than $20,000 per acre. This estimate shows the vulnerability of these estimates to extrapolation but also illustrates the potential for a large willingness to pay if a mechanism could be found to facilitate such contributions.

For giant garter snakes, consider the average total WTP estimate of $106 per household for non-charismatic species. If we interpret the payment of $106 per household as a one-time payment for the approximately 13 million households in California, the total value for the species is about $1.4 billion or about $3,500 per acre of relevant riceland.

These WTP estimates do not mean each household would issue a direct payment to rice growers of that exact amount. Given our example calculations, if the average WTP is relatively high compared to costs, we can say that it would be reasonable to provide at least some amount of wildlife habitat. Determining how much habitat and what payments should be assigned, would depend on a more detailed analysis of the relevant WTP and cost conditions.

6.5 Wildlife values associated with government payment programs

Government programs may reflect informed evaluations of habitat improvements and identify the “value” of similar gains that might be achieved by rice production practices. The California Winter Rice Habitat Incentive Program pays rice producers for continuous flooding of 1-12 inches for 70 days between October 15 and March 15. The annual rates are $15/acre on the East side of the Sacramento Valley, and $30 on the West side (California Ricelands Waterbird Foundation, 2020a). The Fish Food program pays rice producers to flood their fields with 10 inches of water for a minimum of three weeks between October and April to support juvenile Chinook Salmon populations (California Ricelands Waterbird Foundation, 2020b). Similarly, the BirdReturns program uses a bidding process with self-reported costs. Though no per-acre payments are reported, since 2014 BirdReturns has generated over $2 million in farm payments and facilitated over 60,000 acres of bird habitat (The Nature Conservancy, 2024a). This would average out to about $33 per acre. The goal of these programs is to incentivize additional habitat; however, some riceland enrolled may have been flooded as required even without payments.

Recently government farm practice mandates, funded by higher costs to consumers have illustrated indirectly voter willingness to pay as consumers. In 2018 California voters approved a proposition that has mandated the mother sows must be housed in ways that meet specific minimum standards if their baby pigs are destined for California consumers. The cost works out to about $300 million per year (Lee, Sexton, and Sumner (2023).

If Californians care about as much for the aggregate of the birds, fish, and snakes in Northern California as about mother pigs that live in Canada and the Midwest, then we can use the $300 per year willingness to pay as representative of potential for revenue to rice farms to provide incentives for providing quality habitat. For 400,000 rice acres that qualified, the payment would be the equivalent of $750 per acre supplement to revenue.

6.6 Markets for capturing WTP through wildlife-friendly labeling

A wildlife-friendly label on rice packaging may elicit price premiums and changes in consumer purchasing behavior. Retail data on the effects of the dolphin-safe label on tuna consumer behavior showed that the label increased the market share, with an annual effect ranging from $6-15 million (in 1990 dollars) in the United States (Teisl et al, 2002). Loureiro & Lotade (2005) found that fair trade labels for coffee generate large positive WTP estimates compared to regular and organic coffee. Generally, the effectiveness of label claims depends on clarity and credibility.

6.7 Additional considerations

To elicit willingness to pay for riceland, the ecological results must demonstrate the clear link between rice acreage above what would have been planted anyway and how this additional acreage would benefit the species' wellbeing. The cost side of providing more and improved habitat includes alternative uses (the opportunity costs) for relevant land. The benefits of alternative uses of riceland includes profits of alternative crops, but also alternative agricultural and wildlife uses that may provide habitat for other valuable species or other environmental benefits. The tradeoffs include costs saved from water for flooding and benefits from the different species affected. Quantifying economic and ecological alternatives for land, water and other resources used for rice must be part of the broader considerations beyond those of this study.

6.8 References

California Department of Fish and Wildlife. (2023). *2022 Marine Region - By the Numbers*. State of California. https://nrm.dfg.ca.gov/FileHandler.ashx?DocumentID=210781&inline

California Ricelands Waterbird Foundation. (2020). “California Winter Rice Habitat Incentive Program – Practice Requirements.” California Ricelands Waterbird Foundation. https://calricewaterbirds.org/cwrhip/cwrhip-practice-requirements/

California Ricelands Waterbird Foundation. (2020). “Fish Food Program.” California Ricelands Waterbird Foundation. https://calricewaterbirds.org/fish-food/

Christie, M., Hanley, N., Warren J., Murphy, K., Wright, R., & Hyde, T. (2006). Valuing the diversity of biodiversity. *Ecological Economics* 58(2): 304-317. https://doi.org/10.1016/j.ecolecon.2005.07.034

Freeman, A. M., Herriges, J. A. & Kling, C. L. (2014). *The measurement of environmental and resource values: Theory and methods* (3rd ed). RFF Press.

Haefele, M. A., Loomis, J. B., Lien, A. M., Dubovsky, J. A., Merideth, R. W., Bagstad, K. J., Huang, T., Mattsson, B. J., Semmens, D. J., Thogmartin, W. E., Wiederholt, R., Diffendorfer, J. E., López-Hoffman, L. (2019). “Multi-country Willingness to Pay for Transborder Migratory Species Conservation: A Case Study of Northern Pintails.” *Ecological Economics* 157: 321-331. https://doi.org/10.1016/j.ecolecon.2018.11.024

Knoche, S., & Lupi, F. (2007). “Valuing deer hunting ecosystem services from farm landscapes.” *Ecological Economics* 64(2):313-320. https://doi.org/10.1016/j.ecolecon.2007.07.023

Kolstoe, S. & Cameron, T. A. (2017). “The Non-market Value of Birding Sites and the Marginal Value of Additional Species: Biodiversity in a Random Utility Model of Site Choice by eBird Members.” *Ecological Economics* 137: 1-12. https://doi.org/10.1016/j.ecolecon.2017.02.013

Lee, H., R. Sexton, and D. Sumner. 2023. National and subnational regulation of farm practices for consumer products sold within a jurisdiction: California’s Proposition12.” *Agricultural Economics*, 54:838-853.

Lewis, D. J., Kling, D. M., Dundas, S. J. & Lew, D. K. (2022). “Estimating the value of threatened species abundance dynamics.” *Journal of Environmental Economics and Management* 113: 102639. https://doi.org/10.1016/j.jeem.2022.102639

Loureiro, M.L. & Lotade, J. (2005). “Do fair trade and eco-labels in coffee wake up the consumer conscience?” *Ecological Economics* 53(1): 129-138. https://doi.org/10.1016/j.ecolecon.2004.11.002

Massey, D. M., Newbold, S. C., Gentner, B. (2006). “Valuing water quality changes using a bioeconomic model of a coastal recreational fishery.” *Journal of Environmental Economics and Management* 52(1): 482-500. https://doi.org/10.1016/j.jeem.2006.02.001

Matthews, L.J. (2019). “Changing Post-harvest Practices, Impacts on Waste Grain Availability, and Grower’s Perspectives: A study of rice and corn fields for wintering waterfowl in the Central Valley.” Master’s thesis, University of California, Davis.

Nature Conservancy, The. (2024). “About.” BirdReturns. https://birdreturns.org/about/

Nature Conservancy, The. (2024). “Statewide Status – State of Salmon.” State of Salmon in California. https://casalmon.org/statewide-status/

Patton, S. (2018). *National Survey of Waterfowl Hunters: Nationwide and Flyway Comparisons*. Report to the National Flyway Council from the Minnesota Cooperative Fish and Wildlife Research Unit and University of Minnesota. St. Paul, MN 55108

Patton, S. (2021). *National Survey of Birdwatchers: Nationwide and Flyway Comparisons*. Report to the National Flyway Council from the Minnesota Cooperative Fish and Wildlife Research Unit and University of Minnesota. St. Paul, MN 55108

Richardson, L. & Loomis, J. (2009). “The total economic value of threatened endangered and rare species: An updated meta-analysis.” *Ecological Economics* 68(5): 1535-1548. https://doi.org/10.1016/j.ecolecon.2008.10.016

Subroy, V., Gunawardena, A., Polyakov, M., Pandit, R. & Pannell, D. J. (2019). “The worth of wildlife: A meta-analysis of global non-market values of threatened species.” *Ecological Economics* 164: 106374. https://doi.org/10.1016/j.ecolecon.2019.106374

Teisl, M.F., Roe, B., Hicks, R. L. (2002). “Can Eco-Labels Tune a Market? Evidence from Dolphin-Safe Labeling.” *Journal of Environmental Economics and Management* 43(3): 339-359. https://doi.org/10.1006/jeem.2000.1186

7. Synthesis: A Conservation Footprint for California Rice

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California's rice agriculture has enormous impact on the state's economy and employment, contributing over a billion dollars in direct and indirect economic activity and providing over 7,500 jobs. Equally important, California ricelands play a critical role in sustaining a diversity of wildlife and the ecological functions they provide. Indeed, extensive studies over the past two decades have documented the value of ricelands to waterfowl, shorebirds, terns, cranes, snakes, and more recently, native fishes (Table 1.1 Section 1). However, the vast majority of prior studies focus only on single wildlife taxa, each with specific ecological requirements. This report represents a first attempt to develop a fully integrated understanding of the ecological value of riceland, considering the mutual needs and potential compromises for many wildlife species simultaneously. Specifically, our collective expertise in rice agriculture, economics, and one or more of five focal species groups allowed us to address three interrelated objectives:

(1) examine the compatibility of current and emerging rice management practices for conserving diverse wildlife species,
(2) identify priority rice locations for multi-species conservation, and
(3) estimate the 'footprint' of rice acreage needed to sustain desired wildlife species and populations within a viable rice production industry.

In this section, we synthesize and distill key outcomes from our taxa-specific analyses.

7.1 Compatibility of rice management practices

The capacity of California's ricelands to conserve wildlife depends not only on the total acreage, but also how those fields are managed. Each species of wildlife has its own requirements in terms of water availability, water depth, timing of management actions in rice fields, and seasonal chronology that ultimately determine the number of acres and type of management required (summarized in Table 7.1). To determine the total rice footprint needed for conservation purposes, we must first consider the influence of different rice management actions. Which management practices are vital for each species? Can rice acres be shared among taxonomic groups or are the needs of different species so incompatible that rice must be managed in fundamentally different ways for different species? Overall, our analyses suggest that some practices are mutually beneficial for multiple species with minimal conflicts among species. Other practices, however, present potential conflict and thus necessitate compromises, consideration of alternative management practices, or additional acres to pursue multi-species conservation.

Winter flooding

Among all the rice management practices considered, winter-flooding is by far the most valuable for almost every species group. The only taxa for which winter-flooding was not essential were the Giant Gartersnake – because they remain underground in brumation burrows during winter – and breeding Black Tern and shorebirds. Flooding over planted rice is useful for waterfowl and cranes, which utilize residual rice. Flooded fallow fields may still provide roosts for these groups, and they serve fishes and shorebirds that exploit invertebrates rather than rice directly. That said, management practices that reduce organic material and vegetation in the soil might impact the productivity of invertebrates, which may in turn reduce resources for shorebirds, waterfowl, fish, and other species. This is an emerging area of research need.

Table 7.1. Summary of habitat and rice field management suitability requirements for species groups considered in this report.

		Giant Gartersnake	**Waterfowl**	**Shorebirds**	**Shorebirds & Black Tern**	**Sandhill Crane**	**Juvenile Native Fishes**	**Zooplankton[1]**
Habitat Type		Foraging, basking, shelter	Foraging	Foraging	Nesting and Foraging	Roosting	Rearing and Foraging	Production
Target Season		Spring through Fall	Nonbreeding	Nonbreeding	Breeding	Nonbreeding	Winter & Spring	Winter & Spring
Start Date		1-Apr	15-Aug	1-Jul	1-May	1-Oct	1-Jan	1-Oct
End Date		15-Nov	31-Mar	15-May	10-Aug	15-Mar	1-Mar	30-Mar
Planted rice required		Yes	Yes	No	Yes	No	No	No
Target acres (ha) of planted rice	**Min.**	83,634 (33,845)	375,000 (151,757)		>426,043 (>172,414)		30,000 (12,140)	
	Optimum		500,000 (202,342)		472,794 (>191,333)			
Winter flooding required		No	Yes	Yes	No	Yes	Yes	Yes
Target acres (ha) of winter-flooded rice	**Min.**	-	212,002 (85,794)	373,540[2] (151,166)	-	43,139 (17,458)	30,000 (12,140)	
	Optimum	-	257,727 (104,298)		-			
Optimal Water Depth (in)	**Min**	4	>1	>0	>0	>0	6	6
	Upper range	18	10	4	< vegetation height	8	>10	10
Connectivity to Channel Required		No	No	No	No	No	Yes	No

1 We include Zooplankton production in this table because of the increasing interest in producing fish food in flooded rice fields (Section 5.5).

2 This minimum refers to the mid-winter peak of typical winter-flooded rice, and fallowed rice fields can contribute to this total. This minimum does not include any additional targeted flooding during the fall and spring, such as through incentive programs, which also contribute valuable shorebird habitat.

Feasibility - While the value of winter-flooding is clear, challenges exist with respect to long term feasibility and economics. Fewer growers may choose to winter-flood because of increasing water costs and reduced availability, especially during droughts. Instead, some growers are turning to other methods of straw management, such as baling or chopping and incorporating straw but leaving fields dry to decompose straw when naturally inundated by winter precipitation. Trading off against these costs are the potential benefits of revenues obtained from leasing fields and blinds for duck hunting (Section 6). Compared to analyses conducted for the Central Valley Joint Venture's implementation plan, the extent of winter flooding in rice has declined in recent years from averages estimated for 2007-2014, putting more pressure on managed wetlands (Section 5).

We did not evaluate the potential loss of winter-flooding (but see Sections 3, 6). However, a recent analysis of the value of rice fields for waterfowl food production indicates that if flooded rice was not available, replacing that food base would require an additional 255,000 acres of managed wetlands at a cost of nearly $2.8 billion in 2010 dollars (Petrie and Petrik 2010). Adding the additional needs for other species groups (shorebirds, cranes, fish) would only magnify this cost. While the risk of conversion of rice to other crops is low (Section 3), reductions in winter-flooding would significantly impact the value of existing ricelands for many groups of wildlife.

Timing of initial winter flooding

While the optimal timing of initial winter-flooding varies among species, the conflicts that arise are more with water management necessary for rice production rather than conflicts among species, *per se.* A schematic of the months when each species requires winter-flooding, along with the typical schedule for rice field flooding (winter and growing season) is shown in Figure 7.1.

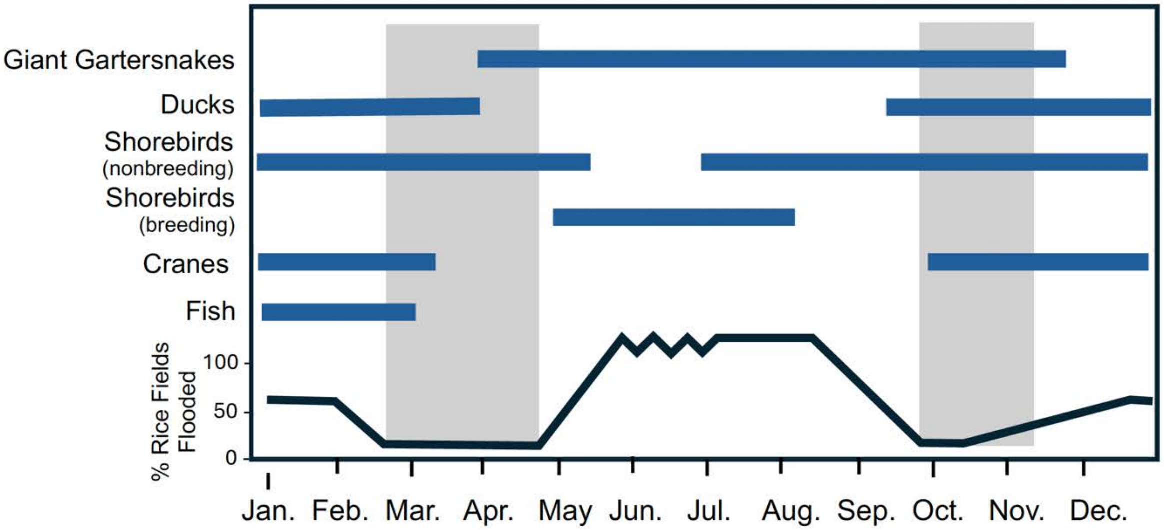

Figure 7.1. Schematic illustration of the timing of winter-flooding and needs for each focal wildlife group. Solid blue bars indicate periods when each species groups needs water in rice fields. The lower black line represents the chronology of flood-up and draining typical in California rice fields. The gray bars represent periods when several species groups require flooded fields but, without other conservation programs, fields would be dry.

Growers that choose to decompose waste grain through winter flooding typically begin flooding their fields in late October-early November. Acreage gradually increases through December. Fields are then drained in early to mid-February. For waterfowl, the greatest need for flooded foraging habitat is from September to the end of February. Flooded rice fields are not available in late September and early October; thus, local breeding birds and early migrating ducks rely heavily on managed wetlands during this period. Duck clubs are often flooded in early October to attract waterfowl prior to the hunting season.

Earlier flood-up in late July and August would clearly be beneficial for migrating shorebirds; however, rice is not harvested until early September through October. This is one of the two shoulder periods when bioenergetic models indicate a significant shortfall of foraging resources for shorebirds in every year (Section 5.3). Sandhill Cranes arrive a bit later than shorebirds, with numbers increasing in September and October. The dry period in October prior to winter-flood-up thus represents a potential bottleneck for cranes. Correspondingly, in all but one scenario (2020-2021; Section 5.4), there was a deficit of roosting habitat for cranes in October.

Managing fishes in rice fields requires a later flood-up schedule, with fish primarily using fields beginning in early January. Early fall flooding has the potential to produce dangerous temperature-oxygen conditions for fishes because of microbial decomposition of organic matter. That said, fish food programs to produce zooplankton could benefit from flooding earlier in October. Finally, as noted, Giant Gartersnakes do not depend on winter flooding; thus, the timing of winter flood-up does not impact them (though the timing of spring flood-up for rice planting certainly does; see below). Nonetheless, dry periods in September and October can impact Giant Gartersnakes, highlighting the importance of having nearby wetlands during this critical period.

Feasibility - Analyses of the timing of winter flood-up suggest that water would be available in late fall and winter for most species. However, the late summer to early fall period is a potential bottleneck for many species (late July-August for shorebirds and the Giant Gartersnake; September-October for Giant Gartersnake, shorebirds, cranes, and ducks). Agronomic constraints limit opportunities for earlier flood-up dates, since rice is still in the growing stages and cannot be harvested until October. Programs to incentivize flooding of fallow fields or uplands during late summer could be critical to support fall migrating shorebirds and the Giant Gartersnake (Halstead et al. 2010, Strum et al. 2013, Migratory Bird Conservation Partnership 2014, Golet et al. 2022). Managed wetlands that are flooded early play a crucial role during the fall dry period. For example, bioenergetic modeling (Section 5.2) indicates that ducks rely heavily on moist-soil seed resources in managed wetlands in September and October before flooded rice becomes available, and shorebirds rely heavily on both semi-permanent and seasonal managed wetlands in July through September (Dybala et al. 2017).

Timing of winter draining and rice planting

Farmers often need to drain fields by mid-February to provide sufficient time for fields to dry for field preparations to take place in March and April. Fields are then flooded and water-seeded from late April through May (with 50% of fields planted by May 12). Consequently, fields are often dry from March to May (Fig. 7.1). This creates challenges for several species. Giant Gartersnakes need water when they emerge from brumation in early April, yet rice fields are dry. This mismatch may reduce survival at a critical time when the snakes need aquatic habitat and food.

Although many species of ducks begin spring migration in late February and March, the end of the winter season is when food supplies are most depleted, meaning that flooded fields could still be important at this time. Most duck clubs, however, are drained at the end of hunting season in late January (Section 5.2). Later draining of rice would also be beneficial to non-breeding, spring migrating, and breeding shorebirds (Figure 7.1). The spring “shoulder” is the second period when there is a significant shortfall of foraging resources for shorebirds (Section 5.3). Using a variable drawdown design, Sesser et al. (2018) found that delaying drawdown by even 3 weeks supported not only more shorebirds, but also more dabbling ducks and long-legged wading birds. Finally, growing fishes in flooded rice and/or producing fish food needs to conclude by March 1 or earlier (Section 5.5).

Feasibility - Despite the potential benefits to multiple species of delayed drawdown, agronomic considerations limit the feasibility of this option. Because of plant growth requirements and the need to dry fields prior to preparation and seeding, it is difficult for growers to delay draining. There are some possible solutions. For example, one possibility is to flood irrigation canals earlier to provide some early habitat and satisfy Giant Gartersnake needs. In addition, programs such as BirdReturns (https://birdreturns.org/about/) and Bid4Birds have emerged to incentivize farmers to flood earlier or keep their fields flooded later for migratory birds if they have the ability to do so if, for example, their fields are planned to be idle or they know they can dry in time. Creating mosaics of rice fields with variable drawdown dates (e.g., Sesser et al. 2018) via appropriate incentives or easements could offset some of the loss of rice production from delayed draining and planting.

Winter flooding depth

Water depth emerged as perhaps the greatest issue of conflict among the five groups of wildlife species. Each taxon has distinct depth requirements for foraging, as illustrated in Figure 7.2 (depth data were derived from multiple sources: Elphick and Oring 1998,Colwell and Taft 2000, Elphick et al. 2010, Strum et al. 2013, Behney 2020, Conlisk et al. 2024).

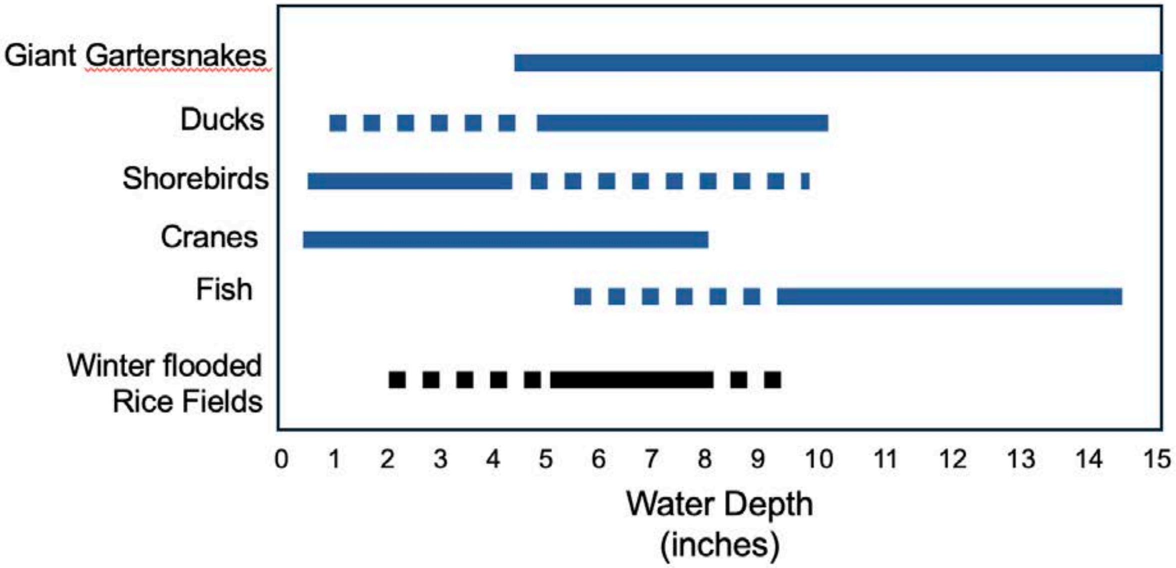

Figure 7.2. Schematic illustrating the range of water depths used for foraging by each species. Solid blue bars represent the typical preferred range of depths, dashed bars show additional depths that can be used but are not preferred. The black bar at the bottom shows the range of depths in most flooded rice fields, with dashed bars representing possible variation due to flooding schedules, evaporation, etc.

Summarizing, shorebirds forage in the shallowest water from 0-4 inches. Some species can forage in deeper water, but depths beyond 8-9 inches are unusable for most species. Cranes likewise can use shallow water to forage. Deeper water can be used for roosting but not foraging. Preferable foraging depths for dabbling ducks are 4-10 inches. Deeper water is not accessible for foraging for most dabbling ducks, but can be used by some diving ducks, although we did not consider diving ducks in this report. Deeper water can be used by ducks for roosting. Giant Gartersnakes prefer water depths of 4-18 inches. Of all groups, fishes require the deepest water of 10-12 inches or deeper in flooded fields.

Feasibility - Differences in depth preferences reveal challenges facing rice growers and conservation managers in providing flooded habitat to meet the needs of all or most species. Depths of 4-8 inches provide suitable depths for Giant Gartersnakes, Sandhill Cranes, and dabbling ducks, but are too deep for many shorebirds and too shallow for fishes. Added to this are agronomic and economic challenges. Deeper flooding requires more water that must be maintained at that depth for three or more months, which can be very costly or even infeasible to obtain. Further, rice levees need to be reconfigured to hold deep water, which also incurs costs to growers. Conversely, if too little water is applied, straw decomposition may be less effective, and ducks would not be attracted, reducing opportunities to lease hunting blinds. Maintaining flood water at a shallow depth and re-irrigating could also be costly. Many growers avoid these costs by flooding more deeply at first and then gradually letting the water draw down.

Possible paths forward might be to create habitat mosaics of flooding depths that could satisfy all constituencies. Snakes could be supported in canals. Fields with a range of flooding depths and durations (e.g., Sesser et al. 2018), including management and flooding of fallow fields (Iverson et al. 2024b) could thus provide a range of conditions that meet the needs for multiple species and minimize additional water use and expense (Strum et al. 2013, Migratory Bird Conservation Partnership 2014, Golet et al. 2022). Fishes remain a concern because of their unique requirement of depths more than 10 inches, but this issue may be spatiotemporally constrained if the objective is only for flooding in the bypasses or flooding for fish food only within a specific distance from an outlet to a fish-bearing channel. That practice, however, will likely lead to additional tradeoffs for fish, farmers, and duck clubs in the bypasses so further consideration will be needed (Sommer et al. 2001, Petrik et al. 2012, Howitt 2013, Suddeth and Lund 2016).

Other rice management considerations

Our work suggests the *timing*, *duration*, and *depth of flooding* represent the most important rice management practices for wildlife conservation in California ricelands. These considerations extend into the growing season. For example, it is important to maintain consistent water levels for nesting Black Terns because active nests may be destroyed by rapidly raising water levels and mid-season draining is likely to increase the risk of nest predation (Shuford et al. 2001; Shuford and Dybala 2017).

Aside from water management, other rice management practices are likely also important, but were beyond the scope of this report. For example, the *method of harvest* (conventional vs. stripper header) and the wide variety of *post-harvest practices* (Section 2) can all affect the amount of residual rice grain available to be used by birds (Miller et al. 1989, Miller and Wylie 1996, Day and Colwell 1998, Elphick and Oring 1998, Elphick et al. 2010b, Fleskes et al. 2012, Strum et al. 2013, Sesser et al. 2016, Matthews 2019, Matthews et al. 2022b). Likewise, straw removal by *baling* or *deep disking* can influence the accessibility of residual rice grain to foraging birds (Matthews 2019).

Agrochemical applications in ricelands could also affect wildlife. Though not studied in California ricelands, agrochemicals are playing an important role in wildlife declines (Köhler and Triebskorn 2013, Hallmann et al. 2014, Li et al. 2020, Rigal et al. 2023, Molenaar et al. 2024). Pathways are complex and context dependent but likely occur via direct toxicity and/or via indirect reductions in invertebrate food bases. Indeed, a growing recognition of the importance of invertebrates in the diets of almost all species groups (Section 5) suggests that additional research is needed on how rice management practices generally affect invertebrate production. As many as 60 different species of arthropods have been recorded in California rice fields (https://agronomy-rice.ucdavis.edu/sites/g/files/dgvnsk11966/files/inline-files/196740.pdf), and a diverse community of invertebrates has been identified in benthic core samples collected in Central Valley wetlands and flooded rice (Dybala et al. 2017). The ecology of these species in Central Valley wetlands and rice fields is poorly understood, despite their importance in the food web. While many of these species do not affect rice, ten are known to reduce rice productivity and yield (California Rice Production Workshop 2018, Espino et al. 2024). Research on the role of rice management practices and other environmental factors in driving the composition, abundance, and productivity of the invertebrate community would be valuable for identifying opportunities to reduce the abundance of specific species known to affect rice production while enhancing the abundance of other invertebrates, thereby increasing the food supply available to many of the species groups addressed here.

Finally, this report focuses on rice management activities, but the value of rice fields to wildlife is clearly influenced by the *quality and quantity of adjacent habitats* (Table 7.1). Nearby wetland areas are essential for foraging and roosting by waterfowl, shorebirds, and cranes, and provide critical foraging habitat in early fall when rice fields are not flooded. Giant Gartersnakes rely on wetland–rice mosaics to support their habitat needs year-round, and the proximity of rice fields to wetlands is critical for their movement and dispersal. If rice fields are isolated from wetlands, other types of land use can pose barriers to gartersnake movement (Section 5.1). Upland areas likewise play a critical role for Giant Gartersnakes in their active season for sheltering, basking, and thermoregulating, as well as critical refuge over winter. Shorebirds, cranes, and waterfowl use uplands for nesting or roosting. That said, the extent to which different types of vegetation, levee/canal management, and maintenance activities affect wildlife use remains unclear.

Integrating multiple species requirements

The ultimate challenge for any multi-species synthesis is to integrate the diverse needs of each group, assess their commonalities, and identify areas of conflict. Ideally, formal multi-objective decision analysis would be used (Kremen and Miles 2012, Ando and Mallory 2012, Garnache 2015, Suddeth and Lund 2016, Dang et al. 2019, Liu et al. 2020b), but that was beyond the scope of our current project. As a first step toward visualizing these tradeoffs, we qualitatively developed radar diagrams (e.g., Kremen and Merenlender 2018) that illustrate how different rice management actions (timing of winter flood-up, depth of water, proximity of wetlands, presence of uplands, post-harvest straw management, and connection to a main river channel) may affect each species group (Figure 7.3). In a multi-purpose optimization (e.g., Suddeth and Lund 2016), the ecological value of each practice would be formally quantified, weighted for each species, and then used in a trade-off optimization analysis. Here, we instead qualitatively use these radar plots as a heuristic to both illustrate the commonalities among species as well as highlight management actions that are specific to a given group or might conflict with the needs of other groups. These radar plots offer three key take-home messages:

(1) Several management practices have strong conservation value for almost all species: winter-flooding, early fall flooding, presence of adjacent wetlands and uplands, and straw management that does not reduce the availability or access to residual rice grain.
(2) Tradeoffs among species and agronomic practices are mostly over water depth and timing of winter flood-up.
(3) The 'kaleidoscopic' nature of the composite plot (Figure 7.3, bottom) illustrates the diversity of requirements and emphasizes that no single management action will suffice for all species. An effective rice conservation footprint will require a mosaic of acres employing a mixture of management actions.

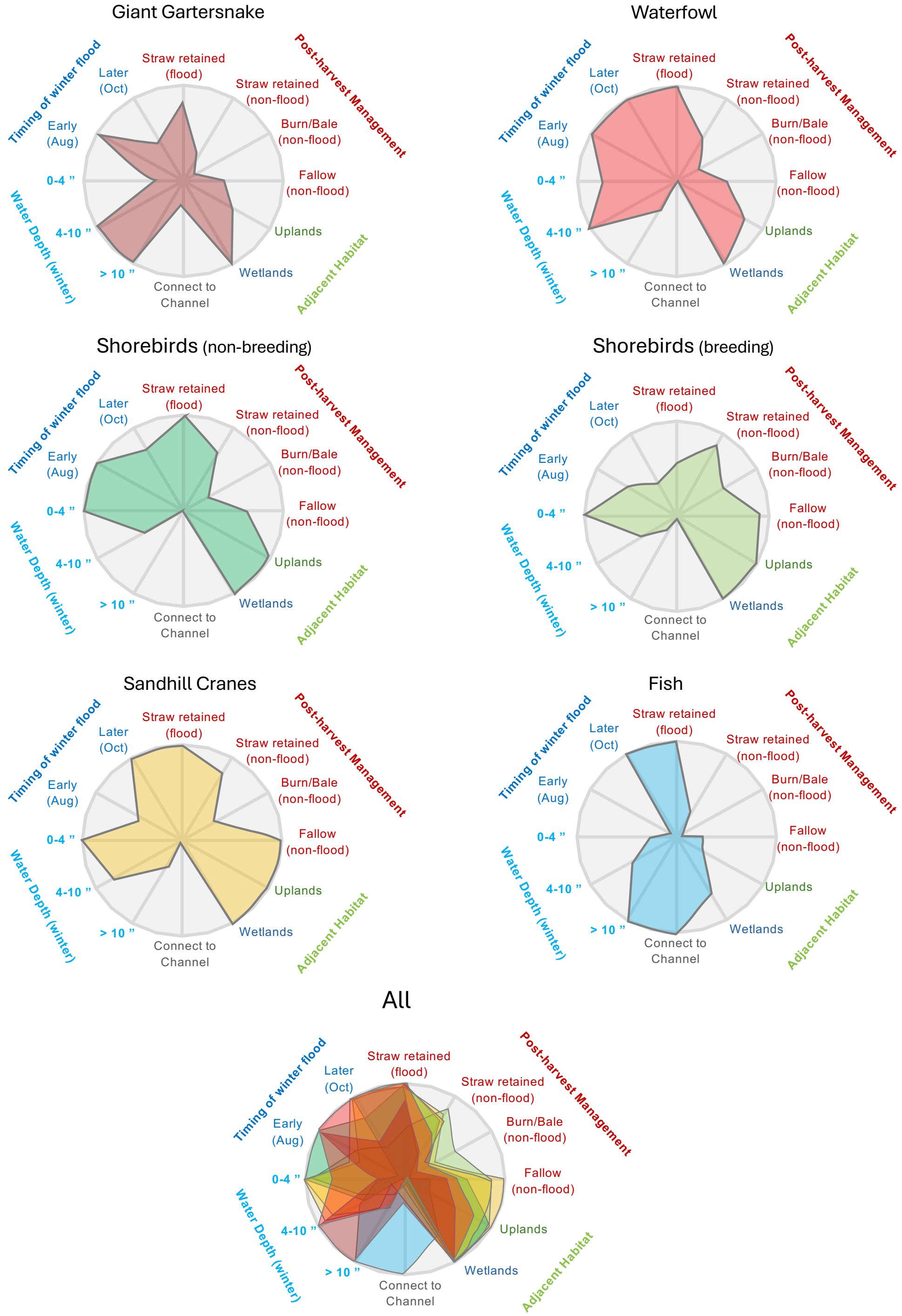

Figure 7.3. Radar diagrams illustrating how different rice management actions (timing of winter flood-up, depth of water, presence of wetlands and uplands, post-harvest straw management, and connection to a main river channel) may affect each group of species. Each axis is graded on a scale of 0-10 from the center origin (relatively little value/importance) to the outer edge (relatively high value/importance). Individual scores will vary depending on the spatial or temporal context and require further refinement. The values shown here are for illustration of the variation among species. The “All” diagram illustrates the potential overlap among all groups.

7.2 Compatibility of locations

Our second objective was to assess priority rice locations for each species. In each of the taxa-specific sections, we employed a variety of modeling and analytical approaches to determine the most important rice regions for each species group (Section 5). To do so, we first generated a common map for all rice fields, other crops, wetlands, and other habitats for four recent years (2020-2024), representing a range of conditions from dry to wet years (Section 4). We also considered the frequency of rice rotation and risk of conversion to other crops (Section 3). Based on these analyses, we identified areas of rice agriculture with high, medium, or low conservation value for each species (see section 5). To identify priority rice locations for conservation across multiple species, we created spatial prioritization maps for ducks, cranes, Giant Gartersnakes (GGS), and shorebirds. These maps (Figure 7.4) highlight high-priority spatial footprints for each taxon, built using criteria outlined in their respective sections. Two adjustments were made for consistency: the GGS spatial footprint was refined by reducing the distance threshold between rice and wetland habitats from 5 miles to 1 mile, and the shorebird prioritization was scaled up from a fine landscape level to agricultural field units, with field units counted as high priority if, in either the breeding or non-breeding season, they either had >15 acres of "High Priority" area or >80% of the patch was "High Priority."

The combined maps (Figures 7.5 and 7.6) aggregate these taxa-specific priorities, displaying the number of species for which each rice patch is classified as high priority. This synthesis offers an overview of multi-taxa overlaps and potential opportunities for joint management. As such, the maps could be useful in:

1. Identifying conservation hubs: Areas near wetland complexes and wildlife refuges emerged as high-priority zones for multiple species, emphasizing their importance as conservation hubs.
2. Highlighting multi-taxa opportunities: Patches classified as high priority for three or more species indicated areas where joint management strategies may maximize conservation benefits.
3. Assessing spatial trends: Regions such as the Sutter and Yolo Bypasses emerged as critical for fishes and other taxa, showcasing the need for tailored management in these areas.

On the other hand, the maps should NOT be used:

1. As an indicator of comprehensive conservation value: These maps are not weighted rankings of conservation value. High-priority areas for multiple taxa are not necessarily of greater overall value than areas critical for a single species.
2. To guide field-level management: The maps do not prescribe specific management actions for individual patches. They lack fine-scale details on habitat quality and current management practices that may influence suitability.
3. To identify areas of low importance: Areas not classified as high priority may still hold significant conservation value, particularly for species or ecosystem services not included in this analysis.

With these caveats, the maps we present would best be used as tools to inform strategic planning and guide conservation discussions. They highlight broad spatial trends and provide a starting point for identifying areas of focus for multi-taxa conservation. For instance, high-priority patches for multiple taxa can indicate areas where joint management might be effective. They also suggest regions that may require more nuanced strategies given potential trade-offs (e.g., deeper water requirements for fish versus shallow water needs for shorebirds). The combined maps also underscore the importance of aligning conservation actions with species-specific needs. For example, while wetlands are critical for all taxa, the water depths required by ducks, cranes, and GGS differ significantly, necessitating tailored water management strategies. Similarly, fish habitat in the bypasses may require careful consideration of water flow, safe and timely passage, flooding duration, and agricultural compatibility.

To improve these prioritization efforts, future work should:
1. Incorporate multi-objective decision analyses to assign relative conservation values, factoring in the feasibility and cost of management actions.
2. Enhance data integration with additional hydrological modeling and fish habitat data to better understand trade-offs.
3. Engage stakeholders in priority areas, including landowners and managers, to translate spatial trends into actionable strategies.

By interpreting these maps within the context of their strengths and limitations, stakeholders can make informed decisions about where and how to focus conservation efforts for maximum impact.

Overall, the mapping effort revealed a high degree of complementarity in priority locations among species. For nearly all species groups, rice acreage in Colusa and Sutter basins, especially near wetlands and wildlife refuges, were often ranked as highest priority (Figure 7.4 and 7.5). Rice fields in Sutter basin and the upper American basin were also high priority for several groups. The Yolo Basin, the Consumnes-Mokelumne Rivers region, and parts of the Delta were important for shorebirds and Sandhill Cranes. The entire Yolo and Sutter Bypasses represent critical areas for fishes in rice fields. Additional rice acres (as yet unspecified) further up the valley could be a priority for fish food programs. The rice footprint, in terms of locations, thus appears complementary among the species groups considered. How those acres are managed, however, is an important determinant of ultimate conservation value (see Section 7.1 above).

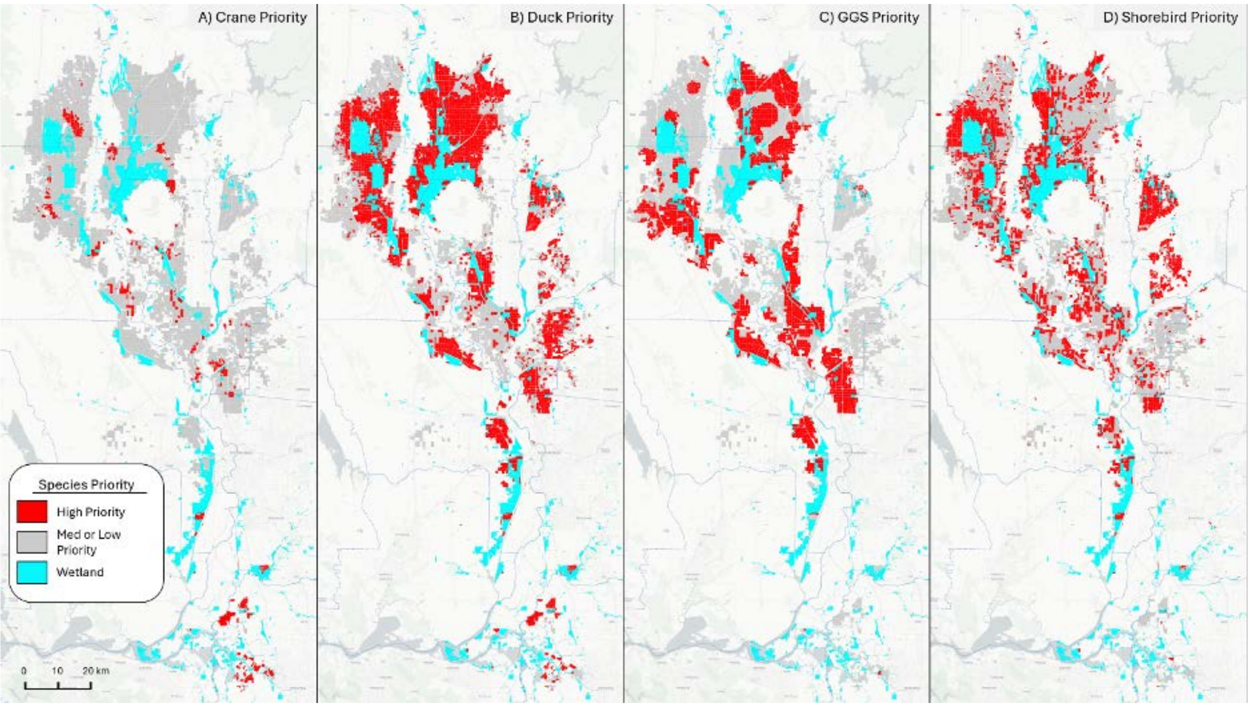

Figure 7.4. Spatial prioritization maps for four taxa groups: (A) Sandhill Cranes, (B) Ducks, (C) Giant Gartersnakes (GGS), and (D) Shorebirds/Black Terns. High-priority rice fields are shown in red, medium or low priority fields in grey, and wetlands in aqua. Each taxon-specific map reflects unique criteria for high-priority designation, as described in the report. Adjustments to the priority maps for GGS and Shorebirds, based on additional proximity and landscape-scale criteria, are detailed in the text. These maps provide essential guidance for habitat management strategies tailored to the needs of each species group.

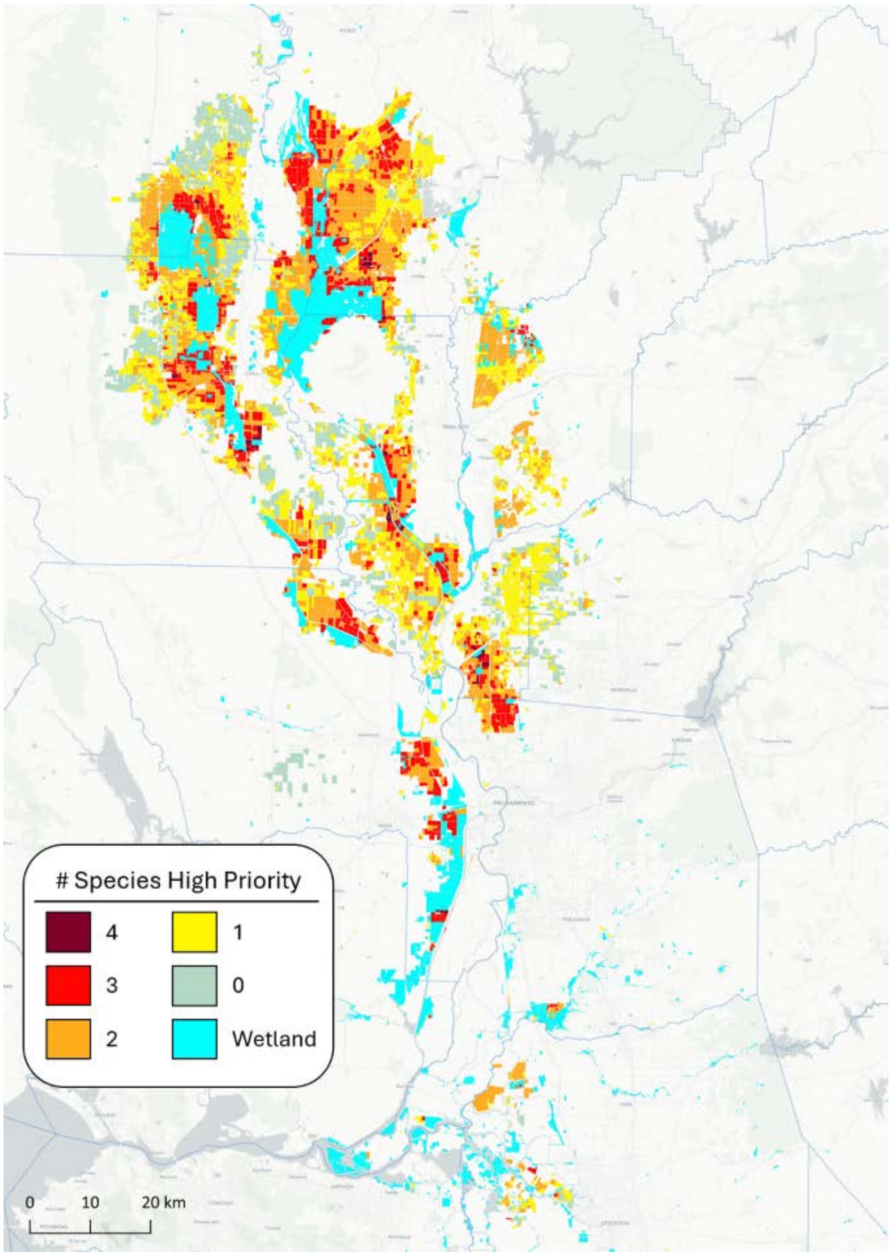

Figure 7.5. Combined priority map for rice fields based on high-priority classifications for four taxa: ducks, Sandhill Cranes, Giant Gartersnakes (GGS), and shorebirds/black terns. Rice fields are colored by the number of taxa for which the patch is considered high priority, with darker/redder colors indicating higher overlap among taxa (dark red = 4 species, red = 3, orange = 2, yellow = 1, green = 0, aqua = wetlands). This map highlights areas where joint management opportunities exist or where trade-offs between taxa may need to be carefully balanced. It provides a spatial framework for considering multi-species conservation efforts but does not assess the relative conservation value of individual patches.

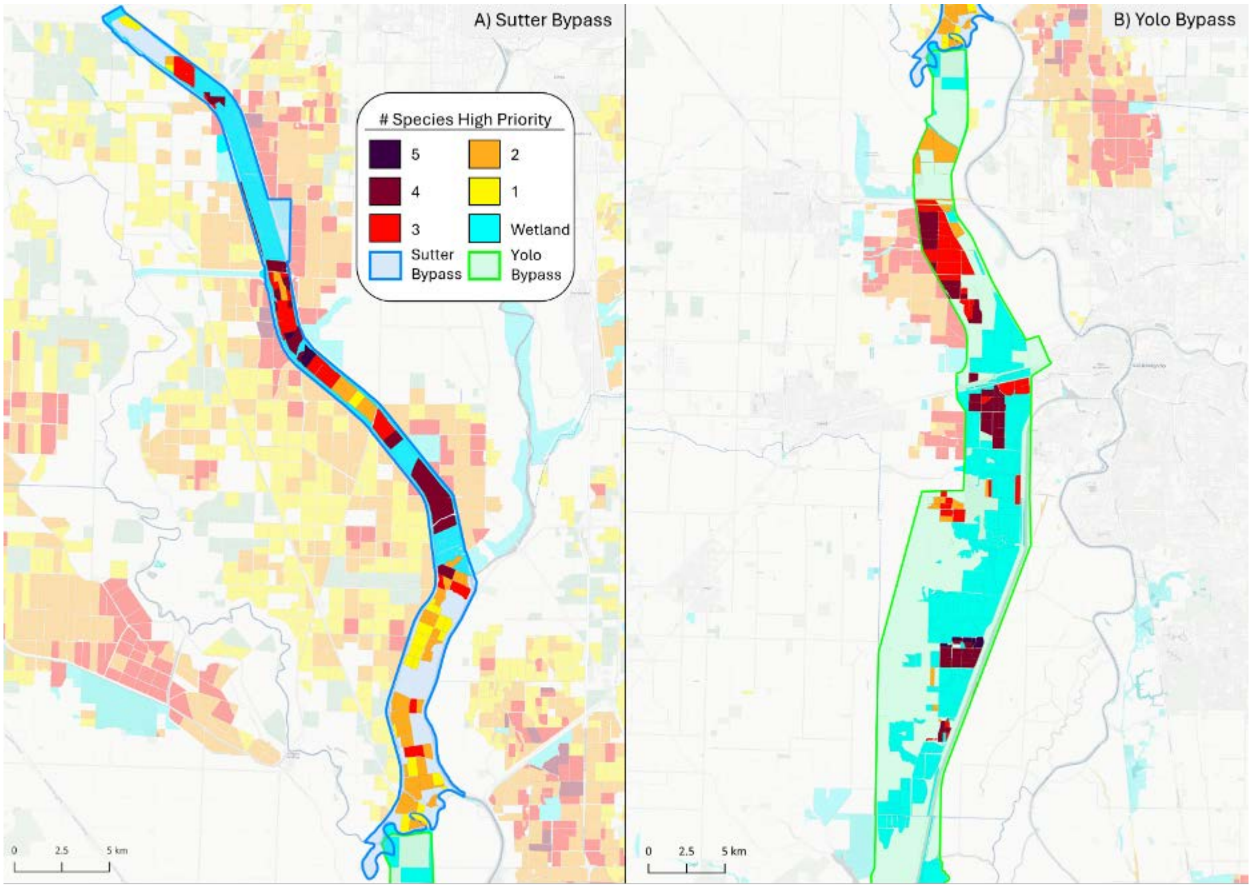

Figure 7.6. Combined priority map for rice fields in A) Sutter Bypass and B) Yolo Bypass, showing multi-taxa conservation priorities. Colors represent the number of species for which the patch is considered high priority, with darker colors indicating more species overlap (dark purple = 5 species, dark red = 4, red = 3, orange = 2, yellow = 1, green = 0, aqua = wetlands). Rice fields within the bypass boundaries receive an additional species priority count due to their inclusion as critical habitat for fishes, as identified in Section 5. The bypasses require careful management to balance water level needs for fishes with the habitat needs of other taxa, such as ducks, cranes, Giant Gartersnakes (GGS), and shorebirds.

Table 7.2. Summary of key priorities and locations of rice acreage to support multiple wildlife species.

	Key priorities	**Locations**
Giant Gartersnake	• fields that have cultivated rice consistently each year • closer to wetland habitat • basins that support Giant Gartersnake populations but where rice has been idled in recent droughts (e.g., south of the Sutter Buttes) • recovery plan target (539-acre wetland paired with 1,578 acres of rice, separated by no more than 5 miles)	High priority acres in Butte, Colusa, Sutter and American Basins; some in Glenn, Yolo, and the Delta.
Non-breeding Waterfowl	• high quality winter-flooded foraging sites • proximity to roosts; roosts serve as ecological hubs due to their proximity to both foraging and resting sites • areas around refuges • lower-priority patches are typically located on basin peripheries	Critical areas in Colusa and Butte basins near the major wildlife areas, smaller priority areas in Glenn County, upper American Basin, Yolo Basin, Cosumnes River
Shorebirds and Black Terns	• during the breeding season, maintain consistent water levels and suitable nest sites • during the nonbreeding season, flooded rice or fallow fields, without dense vegetation, and ideally <4 in • management practices that incorporate rice straw and stubble into the soil may increase invertebrate densities • high priority areas represent only 20% of the rice footprint in 2020-2024, while at least 81% is needed to support Black Tern conservation objectives; all the high and moderate priority areas and a large proportion of the low priority areas are important to these species	Breeding densities highest in Yolo-Delta region for Stilt and Avocet; Black Tern densities were highest in the Sacramento region, especially Glenn and Yuba counties During the nonbreeding season, high priority areas were more dispersed throughout including Colusa, Butte basins near the major wildlife areas, Sutter, upper American Basin, Yolo Bypass, Cosumnes
Sandhill Cranes	• combination of wetlands, non-rice agriculture, and rice; flooded wetland habitat alone is insufficient to support crane roosts at recommended densities • The Yolo-Delta Region has hotspots of high crane roost suitability; 68.9% of the highest-rated potential roost fields were from this Region	Yolo-Delta Region, southeast of Willows, and West of Live Oak.
Fishes	• every acre of bypass fields enrolled in the practice standard is needed to maximally boost salmon populations • flooding of natural habitats [or non-rice areas] would boost this number more, but there are not enough bypass rice acres to approach full replacement • basins south of the Sutter Buttes • 59,600 acres of fish food fields (currently enrolled) • Up to 200,000-300,000 acres potentially on dry side for fish food production	Yolo and Sutter bypass, basins south of the Sutter Buttes Additional acres enrolled in fish food program

7.3 Risk of loss of rice acreage or conversion

We considered the potential loss of rice acreage, either through rice rotations or conversion to other crops, that could significantly reduce the conservation footprint (Section 3; Figure 7.6). The primary rice growing counties of Colusa, Glenn and Butte had very little crop rotation, whereas crop rotation occurred primarily in the southern portion of the Sacramento Valley (mostly in Sutter and Yolo counties). Rotations occurred on only certain types of soil, suggesting only 11% of the continuous rice acreage could potentially support rotations with other crops (Figure 7.6 A and section 3 for details). The conversion of rice to perennial crop systems (*i.e.,* orchards, such as almonds and walnuts) represents a more permanent and long-term change and a greater loss of conservation value. Most replacement of rice with orchard crops has occurred on the periphery of the rice area, although walnuts did replace rice along some of the areas adjacent to the rivers (Figure 7.6 B). Heavy clay soils that make up much of the rice area will likely limit further replacement (Figure 7.6 C). Thus, under current economic conditions, the baseline rice acreage is unlikely to fall below 450,000 acres (see Section 3). This is reinforced by high water demands of permanent crops and the recent projections of challenging economic outlooks for tree fruits and nuts. However, during severe drought in 2022, many rice fields were fallowed, causing the planted acres to drop as low as 256,000 acres. Hence, drought, water availability, and water costs, driven by climate variability, will pose the greatest threats to rice habitat for wildlife and will require a footprint that provides some buffer against these uncertainties.

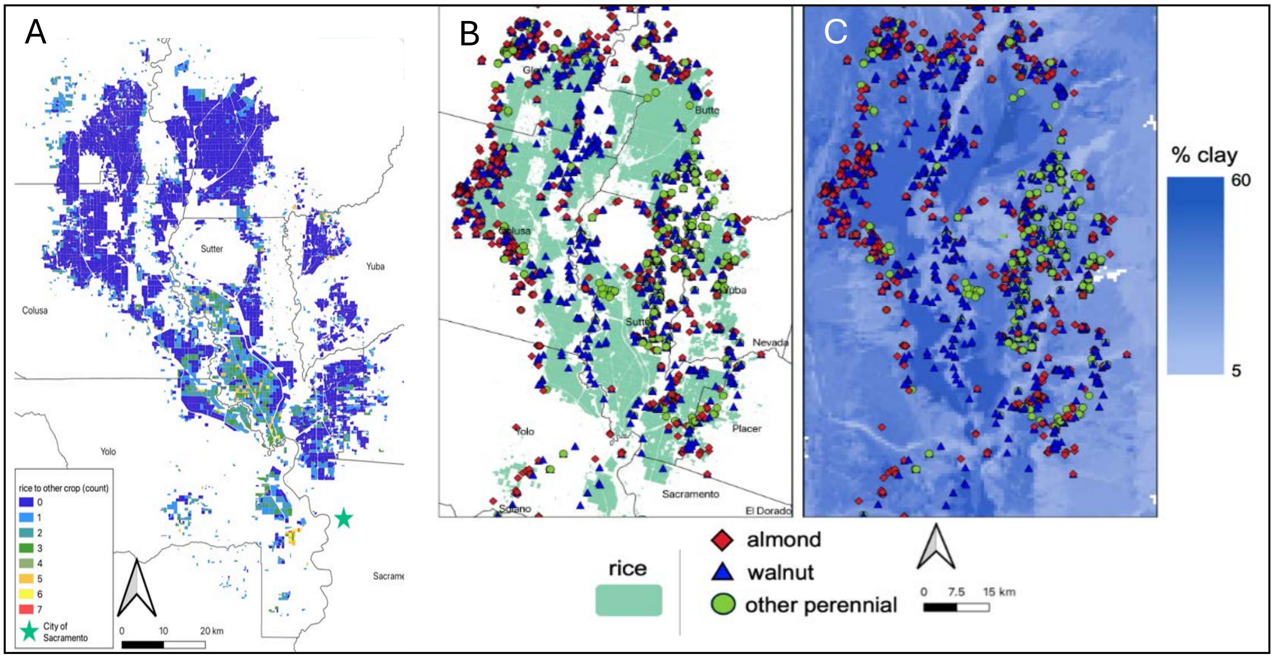

Figure 7.6. (A) Rice rotation frequency map showing the number of times a field changed from rice to alternate crop in a 15- year data set. (B) location of new almond, walnut, and other perennial plantings in the rice growing area and (C) the background clay content (%) in the region (from Section 3).

7.4 The conservation footprint: do we have enough rice in California's Central Valley to support multiple species of wildlife?

Our final objective was to estimate the footprint of rice acreage needed to sustain wildlife species and populations within a viable rice production industry. We caution that this is a rough, or "muddy", footprint as we have not undertaken a formal multi-optimization analysis. Our task instead was to consolidate existing information for several key wildlife species groups, identify critical species needs, their response to rice management practices, and pinpoint locations of rice acreages that would have the greatest conservation value. Having done so, we summarize the acreages needed for each species as follows:

a. **Giant Gartersnake:** 83,634 acres of planted rice is needed to satisfy the recovery plan target habitat objectives There are 158,110 acres that would satisfy these requirements even in a drought year. However, a population viability analysis (PVA) has not yet been completed, and additional acreage may actually be needed, including corridors, uplands, adjacent wetlands, and irrigation canals. Thus, while the current acreage of rice appears sufficient to satisfy recovery plan targets, more research is needed to determine the long-term ability of ricelands to support Giant Gartersnakes. Moreover, how rice is managed (Section 7.10) as well as the distribution of rice fields within a mosaic of habitats, are critical to consider.

b. **Non-breeding Ducks:** ~500,000 planted acres of rice, of which 257,727 acres are winter-flooded, is necessary to ensure resilience under high-competition (HARD) conditions. Alternatively, if competition is assumed to be lower (EASY), then habitat sufficiency could be achieved at 375,000 acres of planted rice, with 212,002 acres that are winter-flooded.

c. **Shorebirds & Terns**: 472,794 acres of planted rice is needed to meet existing conservation objectives for breeding Black Terns, which would also help maintain breeding shorebird populations. Below 472,294 acres there is a high risk of the Black Tern breeding population falling below 1,000 individuals, with increased risk of local extirpation and loss of genetic diversity. The rice footprint needed to support nonbreeding shorebirds depends on the extent that is winter-flooded and can include winter-flooded fallow rice fields. A midwinter peak of flooded rice and fallowed rice of at least 373,540 acres (is needed to maintain support for non-breeding shorebirds. A larger winter-flooded rice footprint above this minimum would contribute to nonbreeding shorebird conservation objectives in the CVJV implementation plan, while footprints below this threshold would increase pressure on managed wetlands. Ultimately, many shorebird populations are 'at-risk', and every additional rice acre would benefit shorebirds.

d. **Cranes**: Sandhill Cranes need 43,139 acres (of flooded acres, which is more than satisfied under current rice acreage. 56,759 acres would be needed if no other roosting habitat was available (which is also currently satisfied). However, there are periods in October when not enough rice is flooded.

e. **Fishes**: All the Yolo and Sutter bypass acres are needed (*i.e.,* 74,000 acres, of which ~30,000 acres are rice). Managing all this acreage for fish would nearly double the Feather River population cohort replacement rate (CRR) from 22% to 38%. Rice alone cannot provide enough habitat for stable populations of fishes, but it can help. Ultimately, we are constrained by the areas of the bypasses for the current practice standard. 54,000 acres of fish food fields (as currently enrolled) could increase the CRR by an additional 6.8%, even with a much-reduced efficacy of the fish food practice relative to the bypass practice. If efficacy is closer to 50%, the CRR jumps to 34%, with no increase in enrolled acreage. These numbers increase substantially as enrolled acreage expands. Future research quantifying the impact of the fish food practice on CRR will be very useful.

If we were to establish the minimum rice footprint to meet the needs of all species, it could be determined as that which satisfies the minimum needs of the species with the largest acreage requirement - any reduction of rice below that target would impact at least that one species. Under this premise, waterfowl (500,000 planted acres) and shorebirds (472,794 planted acres) have the greatest needs and so a minimum footprint of ~470,000– 500,000 acres would define the conservation footprint. Adding in the acreage of rice in the Yolo and Sutter Bypass for fishes (30,000 ac.), the total estimate would be 500,000– 530,000 acres.

However, there are several caveats to this approach. First, these acres represent the optimum to ensure that wildlife are buffered against unpredictable conditions (e.g. dry years, increased competition by geese, etc.). For both waterfowl and shorebirds, we also determined the minimum number of acres that would represent a lower threshold, below which significant population impacts would occur under all environmental conditions. These values are 10-25% lower (375,000 acres of planted rice for waterfowl, 426,043 acres for shorebirds). Between these two extremes is a region which is less than ideal and subject to impact of harsh conditions, but not necessarily catastrophic. We can envision these as zones of *high risk* (red) - where the amount of rice habitat is inadequate under all conditions, *insufficient* (yellow) - where there is risk of not meeting population objectives, especially when conditions are poor, and *sufficient* (green) - where there is enough rice habitat to buffer populations under almost all conditions. We present examples for waterfowl (Figure 5.2.2) as well as shorebirds and Black Terns (Table 5.3.1). This may be a more realistic approach to setting footprint goals, since environmental conditions always vary, and the ability to consistently meet goals that reach or exceed optimum levels of sufficiency (green) may be difficult.

Second, while we refer to the footprint as planted rice acres, for most of the species considered it is the *number of flooded acres* that matters most. 500,000 acres of rice will provide limited conservation value to most species if left dry in fall and winter. Accordingly, the threshold values for waterfowl would be 212,002 acres (red) to 255,727 (green) of winter-flooded rice while the threshold for shorebirds would be 373,540 acres of winter-flooded fields (be it flooded rice fields or flooded fallows). Ensuring the ability to provide winter-flooding will be essential to maintaining a viable conservation footprint for wildlife in the Central Valley.

Third, even though rice acreage currently appears to be adequate for the Giant Gartersnake and Sandhill Cranes, the availability, proximity, and quality of adjacent habitats will influence the conservation value of existing rice acreage significantly. We did not consider changes in the availability or quality of other important wildlife habitat (e.g. wetlands and uplands) but this clearly needs to be addressed. Equally important are the rice management practices on rice acres, especially the timing of flooding and water depths. Currently, we lack spatially-explicit data on the management actions for each rice field, but a future footprint should incorporate this variation.

Finally, our analysis of the needs of fishes in rice fields focused primarily on the bypasses, which also has conservation value for Giant Gartersnakes, shorebirds, ducks, and cranes (Figure 7.4). We simply treated all those rice acres as part of the conservation footprint, but we did not evaluate the tradeoffs of management practices on those acres (e.g. timing and depth of flooding). This is a topic of considerable discussion (Sommer et al. 2001, 2001, 2020, Petrik et al. 2012, Howitt 2013, Suddeth and Lund 2016) and we defer to those analyses. It is worth noting, though, that the same tradeoffs considered in the Yolo Bypass will ultimately need to be assessed for other rice acreage elsewhere in the valley as programs such as Floodplains Reimagined (https://floodplainsreimagined.org) or Fish Food Program (https://calricewaterbirds.org/fish-food/) develop.

7.5 The agronomics and economics of conservation efforts for multiple species

It is one task to prescribe the desired number of rice acres to support wildlife conservation in the Central Valley. It is an entirely more challenging task to evaluate the social and economic capital necessary to support these ricelands and wildlife-friendly management practices. How do farmers, conservationists, and the public value wildlife conservation on ricelands, and most importantly, is the broader public also willing to support these efforts financially and politically? To provide some perspective, we used several methods to project alternative measures of the perceived benefits of improved and expanded habitats for critical species (Section 6): (i) willingness to pay for improved habitat for wildlife species, (ii) willingness to pay associated with use values rather than simply existence value, (iii) wildlife values associated with government payment programs, and (iv) wildlife-friendly label on rice packaging. Some key results were:

- Willingness to pay (WTP) estimates for individual species ranged from $572 per household for charismatic species to $106 per household for non-charismatic species.
- Regional estimates of WTP ranged between $0.08 and $0.18 per household for a one-year population increase of 1000 fish for Oregon Coast Coho Salmon, and $28.46 per US household to improve habitat for Northen Pintail.
- 89% of rice farmers and landowners allowed waterfowl hunting on their property, with 27% of the respondents collecting payment from hunting leases.15% of hunter survey respondents donated between $250-$999, and 5% donated $1000 or more. 4% of birdwatchers donated $250-$999, and 1% donated $1000 or more.
- Some government programs pay $15-30 per acre for continuous flooding programs with specific conditions to support wildlife (California Winter Rice Habitat Incentive Program). The Fish Food program pays rice producers to flood their fields to support juvenile Chinook Salmon. BirdReturns generated over $2 million in farm payments and facilitated over 60,000 acres of bird habitat since 2014 (The Nature Conservancy, 2024a), averaging to about $33 per acre.
- Finally, wildlife-friendly label on rice packaging may elicit price premiums and changes in consumer purchasing behavior. The dolphin-safe label on tuna consumer increased the market share, with an annual effect ranging from $6-15 million.

With this background, we performed a series of illustrative valuation calculations for wildlife in California rice fields. Applying the estimate of $28.46 per household for Northern Pintails to 13 million California households results in a value of *$369.98 million*. Assuming rice comprises 60% of waterfowl food sources, rice fields contribute *$221.99 million* yielding approximately $*554.98 per acre* for permanent access to rice fields. Replacing the food base for waterfowl provided by winter-flooded rice would require an additional 255,000 acres of managed wetlands at a cost of nearly *$2.8 billion* in 2010 dollars (Petrie and Petrik 2010).

For Giant Gartersnakes, a one-time payment of $106 per household for non-charismatic species for the approximately 13 million households in California would result in a total value for the species of about $*1.4 billion* or $*3,500 per acre* of relevant riceland. In a related context, California voters strongly supported improved “habitat” of farm housing for mother sows that will cost Californians about $300 million per year in higher food prices (Lee, Sexton and Sumner, 2023). That amount applied to riceland could add $750 per acre per year for 400,000 acres of rice that committed to provide appropriate habitat along with growing rice.

These evaluations indicate a strong expressed and sometimes actual willingness to pay to support wildlife conservation in ricelands. To be effective, however, the ecological results must demonstrate the clear link between rice acreage above what would have been planted anyway and how this additional acreage would benefit the species' wellbeing. Quantifying economic and ecological alternatives for land, water and other resources used for rice must be part of the broader considerations for future analysis.

7.6 Next steps

In each of our taxa-specific sections, we identified key uncertainties and important research needs for each species group, and we refer readers to those sections for details. Across all species, several cross-cutting research needs and next steps emerged:

1. Despite our focus on several well-known species of conservation and management concern, there is still a dearth of important science/natural history information for several species and/or for portions of their life history. The knowledge base is far more developed for some than others (*e.g.* waterfowl compared to Giant Gartersnake), in part a legacy of past state and federal focus and, in part, due to differences in the ability to survey, monitor, and follow populations. Additionally, there are many other species that use rice fields but were not included in this analysis (e.g., breeding waterfowl, wading birds, rails, wetland associated passerines, mammals, amphibians, other reptiles, and invertebrates), all of which might benefit from or be impacted by the rice footprint.
2. A focus of our analysis was to explore the compatibility of ecological needs among the species and the impacts of different rice management practices, yet there is much more that could be done to better understand the compatibility of rice acres among groups. For example, the different water depths required for each species was a key factor that conflicted most among groups, yet all rice mapping assumed either status quo (i.e., the current range of depths in rice fields) or that water depths would be sufficient. This is clearly not the case. Future analyses will require detailed water depth maps for flooded acres, including spatial and seasonal variation. Admittedly, this is a huge challenge although efforts are underway. Doing so would not only provide far more precise assessments of compatibility of locations but given the mosaic of habitats and depths needed to accommodate all species, we suspect that the conservation footprint would only be larger.
3. Our analysis, by design, provides a "muddy" footprint. We were successful in establishing management practices that support (or limit) wildlife use, identifying locations of high priority ricelands, and providing an estimate of minimum and optimum rice acreage needed to support the wildlife groups we considered. We recommend formal multi-objective decision making and/or multi-purpose optimization analyses as a next step. Doing so would enable a quantitative evaluation of the tradeoffs of alternative conservation and management actions for rice fields in the Central Valley. Our analyses provide a solid starting point for such an approach.
4. Finally, we show that there is much potential support and a willingness to pay (WTP) for wildlife conservation in California rice. To move forward, in-depth surveys and analysis of economic outcomes, impacts, and WTP are needed, along with policy development and multi-stakeholder programs to support and enhance the conservation rice footprint.

7.7 References

Ando, A. W., and M. L. Mallory. 2012. Optimal portfolio design to reduce climate-related conservation uncertainty in the Prairie Pothole Region. Proceedings of the National Academy of Sciences 109:6484–6489.

Behney, A. C. 2020. The influence of water depth on energy availability for ducks. The Journal of Wildlife Management 84:436–447.

Colwell, M. A., and O. W. Taft. 2000. Waterbird communities in managed wetlands of varying water depth. Waterbirds 23:45–55.

Conlisk, E. E., G. H. Golet, M. Reynolds, N. Elliott, and M. E. Reiter. 2024. Factors influencing shorebird use of post-harvest flooded rice fields in California's Sacramento Valley. The Journal of Wildlife Management 88:e22661.

Dang, K. B., W. Windhorst, B. Burkhard, and F. Müller. 2019. A Bayesian belief network – based approach to link ecosystem functions with rice provisioning ecosystem services. Ecological Indicators 100:30–44.

Elphick, C. S., and L. W. Oring. 1998. Winter management of Californian rice fields for waterbirds. Journal of Applied Ecology 35:95–108.

Elphick, C., O. Taft, and P. M. Loureno. 2010. Management of rice fields for birds during the non-growing season. Waterbirds 33:181–192.

Garnache, C. 2015. Fish, farmers, and floods: Coordinating institutions to optimize the provision of ecosystem services. Journal of the Association of Environmental and Resource Economists 2:367–399.

Golet, G. H., K. E. Dybala, M. E. Reiter, K. A. Sesser, M. Reynolds, and R. Kelsey. 2022. Shorebird food energy shortfalls and the effectiveness of habitat incentive programs in record wet, dry, and warm years. Ecological Monographs 92:e1541.

Hallmann, C. A., R. P. B. Foppen, C. A. M. van Turnhout, H. de Kroon, and E. Jongejans. 2014. Declines in insectivorous birds are associated with high neonicotinoid concentrations. Nature 511:341–343.

Halstead, B. J., G. D. Wylie, and M. L. Casazza. 2010. Habitat suitability and conservation of the giant gartersnake (Thamnophis gigas) in the Sacramento valley of California. Copeia:591–599.

Howitt, R. 2013. Agricultural and Economic Impacts of Yolo Bypass Fish Habitat Proposals.

Iverson, S. A., C. Hickey, and K. Sesser. 2024. Rice fallowing and wildlife: Minimizing impacts and increasing opportunity for wildlife due to rice fallowing and rotation in the Sacramento Valley. Point Blue Conservation Science, Petaluma, CA.

Köhler, H.-R., and R. Triebskorn. 2013. Wildlife Ecotoxicology of Pesticides: Can We Track Effects to the Population Level and Beyond? Science 341:759–765.

Kremen, C., and A. M. Merenlender. 2018. Landscapes that work for biodiversity and people. Science 362:eaau6020.

Kremen, C., and A. Miles. 2012. Ecosystem services in biologically diversified versus conventional farming systems: benefits, externalities, and trade-offs. Ecology and Society 17:40.

Li, Y., R. Miao, and M. Khanna. 2020. Neonicotinoids and decline in bird biodiversity in the United States. Nature Sustainability 3:1027–1035.

Liu, X., B. R. Bakshi, B. Rugani, D. M. de Souza, J. Bare, J. M. Johnston, A. Laurent, and F. Verones. 2020. Quantification and valuation of ecosystem services in life cycle assessment: Application of the cascade framework to rice farming systems. Science of the Total Environment 747:141278.

Migratory Bird Conservation Partnership. 2014. Waterbird Habitat Enhancement Program: California Rice Commission.

Molenaar, E., W. Viechtbauer, J. van de Crommenacker, and S. A. Kingma. 2024. Neonicotinoids Impact All Aspects of Bird Life: A Meta-Analysis. Ecology Letters 27:e14534.

Petrie, M. J., and K. L. Petrik. 2010. Assessing waterbird benefits from water use in California Ricelands:12.

Petrik, K., M. Petrie, A. Will, J. McCreary, and F. E. P. Team. 2012. Waterfowl Impacts of the Proposed Conservation Measure 2 for the Yolo Bypass–An effects analysis tool.

Rigal, S., V. Dakos, H. Alonso, A. Auniņš, Z. Benkő, L. Brotons, T. Chodkiewicz, P. Chylarecki, E. de Carli, J. C. del Moral, C. Domşa, V. Escandell, B. Fontaine, R. Foppen, R. Gregory, S. Harris, S. Herrando, M. Husby, C. Ieronymidou, F. Jiguet, J. Kennedy, A. Klvaňová, P. Kmecl, L. Kuczyński, P. Kurlavičius, J. A. Kålås, A. Lehikoinen, Å. Lindström, R. Lorrillière, C. Moshøj, R. Nellis, D. Noble, D. P. Eskildsen, J.-Y. Paquet, M. Pélissié, C. Pladevall, D. Portolou, J. Reif, H. Schmid, B. Seaman, Z. D. Szabo, T. Szép, G. T. Florenzano, N. Teufelbauer, S. Trautmann, C. van Turnhout, Z. Vermouzek, T. Vikstrøm, P. Voříšek, A. Weiserbs, and V. Devictor. 2023. Farmland practices are driving bird population decline across Europe. Proceedings of the National Academy of Sciences 120:e2216573120.

Sesser, K. A., M. Iglecia, M. E. Reiter, K. M. Strum, C. M. Hickey, R. Kelsey, and D. A. Skalos. 2018. Waterbird response to variable-timing of drawdown in rice fields after winter-flooding. PLOS ONE 13:e0204800.

Sommer, T., B. Harrell, M. Nobriga, R. Brown, P. Moyle, W. Kimmerer, and L. Schemel. 2001. California's Yolo Bypass: Evidence that flood control Can Be compatible with fisheries, wetlands, wildlife, and agriculture. Fisheries 26:6–16.

Sommer, T., B. Schreier, J. L. Conrad, L. Takata, B. Serup, R. Titus, C. Jeffres, E. Holmes, and J. Katz. 2020. Farm to fish: Lessons from a multi-year study on agricultural floodplain habitat. San Francisco Estuary and Watershed Science 18:1–20.

Strum, K. M., M. E. Reiter, C. A. Hartman, M. N. Iglecia, T. R. Kelsey, and C. M. Hickey. 2013. Winter management of California's rice fields to maximize waterbird habitat and minimize water use. Agriculture, Ecosystems & Environment 179:116–124.

Suddeth, R., and J. Lund. 2016. Multi-Purpose Optimization for Reconciliation Ecology on an Engineered Floodplain--Yolo Bypass, California, USA. San Francisco Estuary and Watershed Science 14.

Appendices

A1. California Rice Agronomics, Economics, and Conversion Risk

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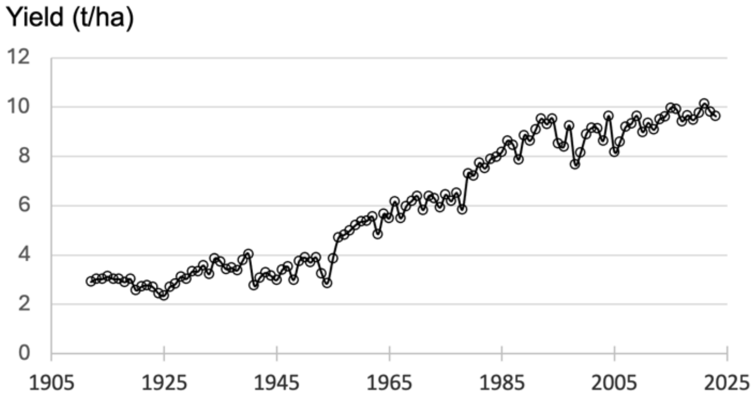
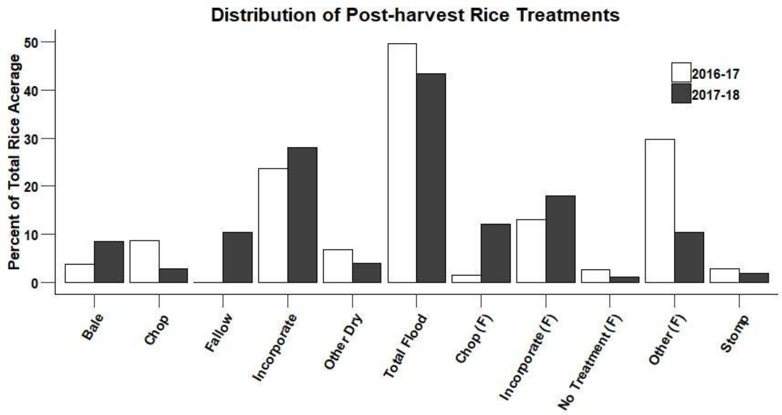
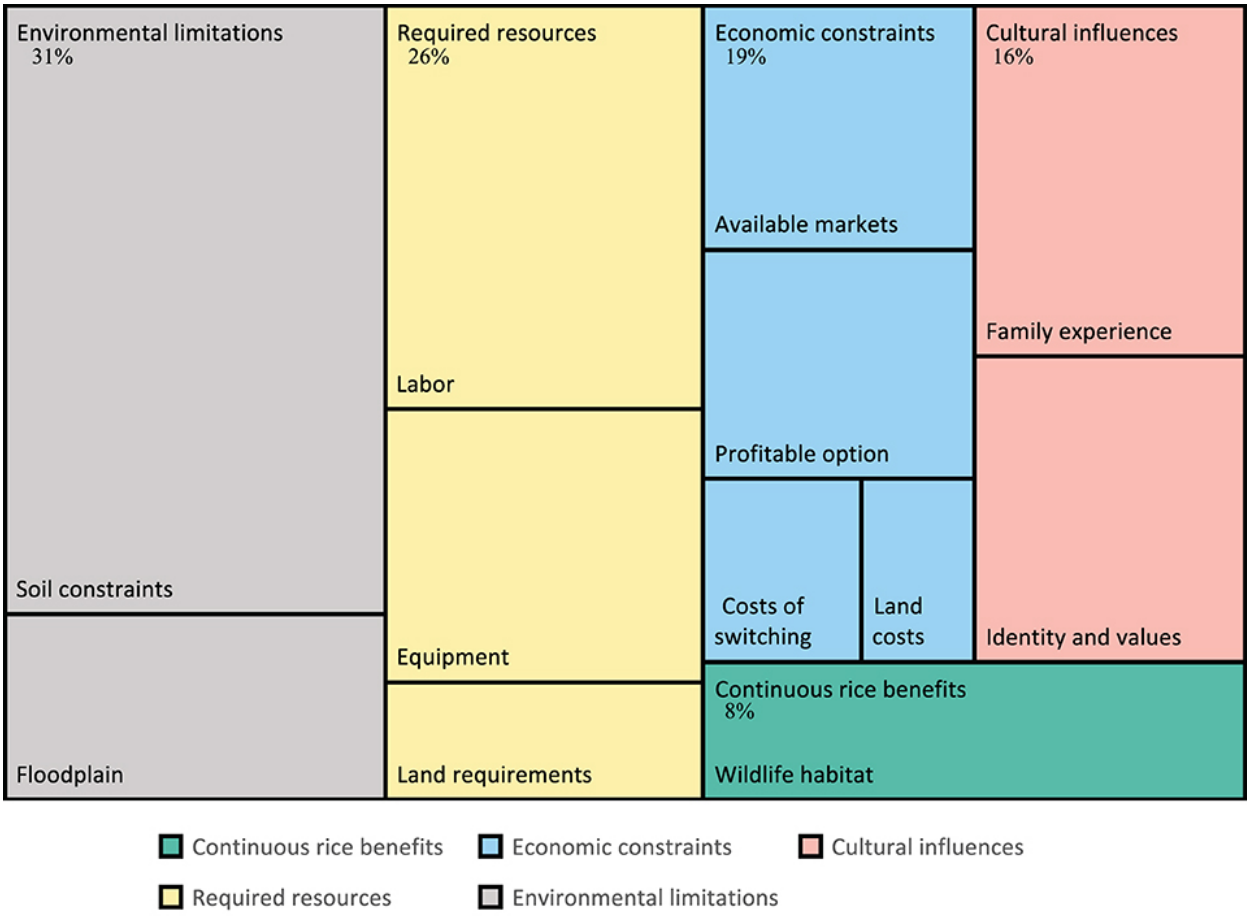


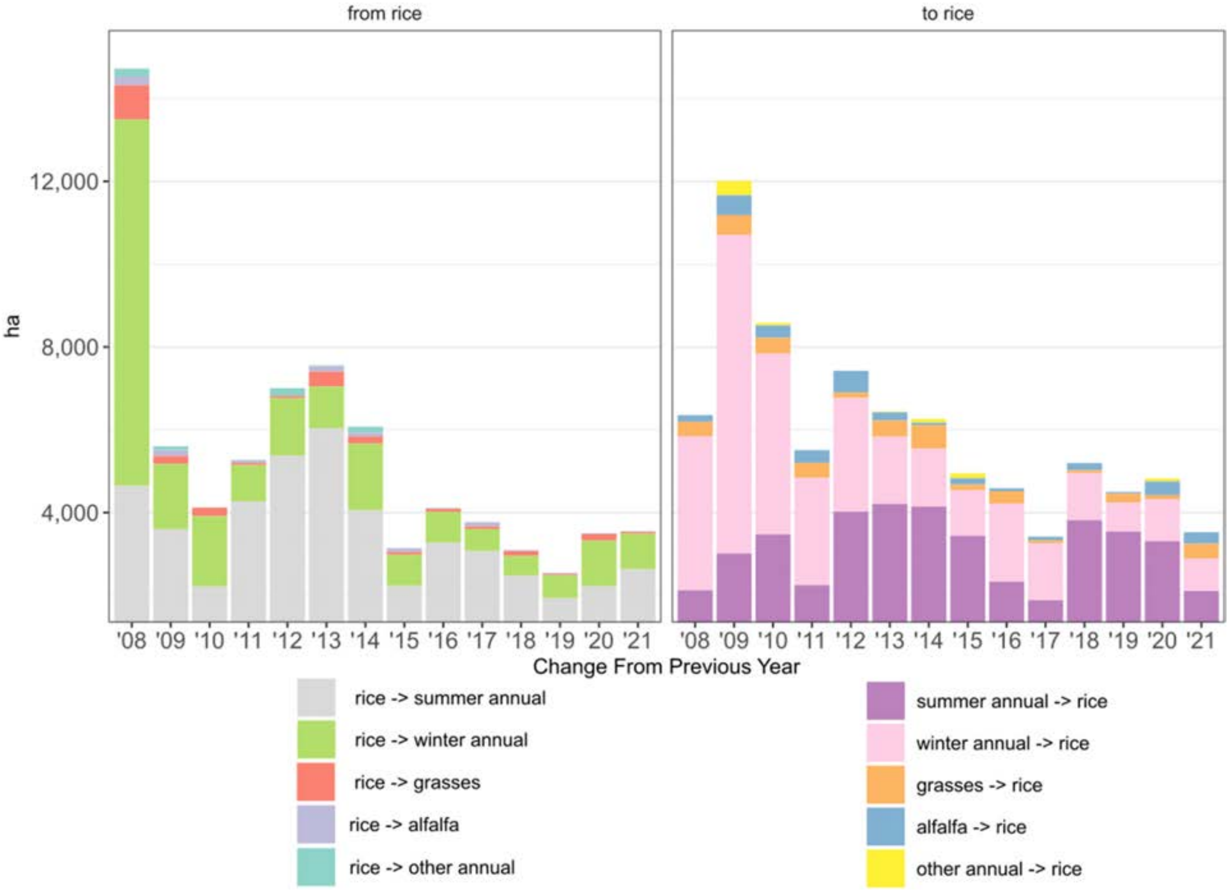
Appendix Fig. 3.1: California rice yields from 1912 to 2023. (1 t/ha = 8922 lb./ac).



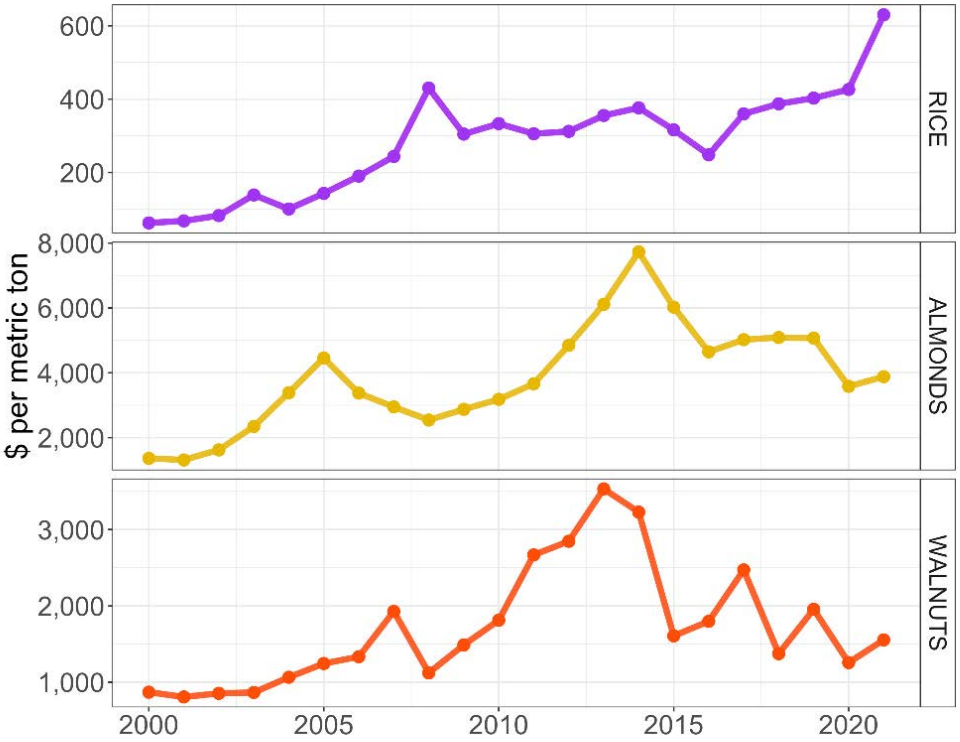
Appendix Fig. 3.2: Distribution of Post-harvest Rice Treatments from Matthews (2019). This figure is a summary of the most prevalent post-harvest treatments used in both 2016-17 and 2017-18. Bale, Chop, Fallow, and Incorporate represent dry postharvest treatments. Total Flooded is a sum of all flooded acreage regardless of prior post-harvest treatment. The last 5 bars reflect a breakdown of post-harvest treatments within flooded fields, with (F) indicating flooding.



Appendix Fig. 3.3: Barriers to adoption for integrating crop rotations into rice systems. The size of each square is based on the number of references coded under each theme (indicated by%). The rank of most significant barriers was: environmental barriers (included soil limitations and the risk of farming on floodplains), economic barriers (included the lack of markets for other crops, lack of other profitable options they could grow, prohibitive operational costs (cost of switching) and overhead costs), resource barriers (included on-farm limitations such as not having the correct labor or management capacity, lacking correct equipment, and not having enough land), cultural barriers (included family experiences and grower identity/values), and continuous rice benefits (includes wildlife habitat which rotations may compromise).



Appendix Fig. 3.4: Yearly area exchanged between rice and annuals, other annuals, grasses, and alfalfa from the 15-year data set.



Appendix Fig. 3.5: Time series of annual price (dollar per metric ton) information for rice, almonds, and walnuts. Crop prices are adjusted for inflation.

A2. Nonbreeding Waterfowl - Rice Mapping and Duck Population Analysis

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1. Introduction

Waterfowl populations in California's Central Valley are critically dependent on managed wetlands and agricultural landscapes, particularly flooded rice fields, for winter foraging habitat. However, fluctuations in agricultural practices and water availability impact the capacity of these landscapes to support migratory species like ducks. The primary objective of this project is to determine how much rice acreage is necessary to sustain the duck population throughout the winter season in the Central Valley. This assessment will provide crucial insights for habitat management, conservation efforts, and agricultural planning, particularly in light of increasing variability in environmental conditions.

California's Central Valley is one of the most important wintering areas for waterfowl along the Pacific Flyway, supporting millions of ducks each year. Historically, extensive wetland complexes provided ample habitat for these birds, but over time, the conversion of wetlands to agricultural and urban uses has significantly reduced the availability of natural habitats. Flooded rice fields now play a vital role as a surrogate for these lost wetlands, providing critical foraging opportunities for wintering ducks. However, the amount and timing of rice field flooding can vary widely due to economic, regulatory, and environmental factors, making it necessary to assess how these fluctuations impact waterfowl populations.

This study is particularly urgent because recent years have seen increasing pressures on both water availability and agricultural viability in California. Climate change is contributing to more frequent and severe droughts, which in turn affect water allocations for both agriculture and managed wetlands. Additionally, economic and regulatory challenges are influencing the timing and extent of rice field flooding. As the reliability of these habitats becomes more uncertain, understanding the specific requirements for sustaining duck populations is crucial for informing adaptive management strategies that can ensure long-term habitat resilience.

Our approach centers on evaluating three key factors that determine habitat sustainability for ducks:

1. **Wetland and Rice Acreage Available for Foraging**: The availability of flooded habitat is a primary factor in determining how much food is accessible to the wintering duck populations. We examine multiple habitat scenarios that vary in both wetland and rice acreage to understand the impact of these variations on duck foraging success. This includes assessing the differences between years with high and low rice acreage, as well as the contribution of managed wetlands to overall habitat availability.

2. **Goose Foraging Pressure**: Geese and ducks share the same foraging landscapes, and geese can exert significant competitive pressure on food resources. To capture this effect, we simulate different goose scenarios—ranging from 100% of geese feeding on rice and corn fields (Goose100) to scenarios where geese receive less of their diet from these resources (Goose75 and GooseScaled). Understanding the extent of this competition is

crucial, as geese can deplete food resources more quickly, potentially leaving ducks with insufficient forage later in the winter season.

3. **Duck Population to be Sustained**: The ultimate measure of habitat adequacy is whether it can sustain the target duck population. In this analysis, we also examine different duck population scenarios for a single habitat and goose condition (the 2122 scenario with Goose100). This allows us to assess whether the available habitat is sufficient to meet the population goals set by conservation guidelines, such as those outlined by the Central Valley Joint Venture (CVJV). The CVJV sets ambitious targets for duck populations, and our analysis aims to determine if current and future habitat conditions can meet these targets.

By analyzing these three factors, we aim to provide a clear understanding of how different habitat and interspecies competition scenarios influence the ability of the Central Valley to sustain duck populations. This report compares the outcomes across different years and scenarios, providing an integrative approach to understanding the dynamic interplay between agriculture, habitat availability, and waterfowl conservation in California's Central Valley. Ultimately, our findings will help inform stakeholders, including farmers, conservationists, and policymakers, about the necessary conditions to balance agricultural production with effective waterfowl habitat conservation.

2. Methods

2.1 Study Area and Scenario Generation

The study area for this analysis is the rice-growing region of California's Central Valley, which serves as a critical wintering ground for millions of migratory waterfowl along the Pacific Flyway. Extending from approximately Red Bluff in the north to Stockton in the south, the study area includes six major basins: Colusa, Butte, American, Sutter, Yolo, and Delta. These basins align with the planning regions identified in the Central Valley Joint Venture (CVJV) 2020 implementation plan, which also groups them into broader categories, such as the Sacramento Valley and Yolo-Delta.

Spanning about 20,000 square miles, the Central Valley features a diverse mix of agricultural fields, managed wetlands, and urban areas. Over time, agricultural development has transformed the region, and flooded rice fields now play a crucial role as a surrogate for the natural wetland habitats that have largely been lost. Figure 1 shows a map of the region, highlighting the parceled landscape with consensus land cover for each parcel over the four years of available data, shown by color.

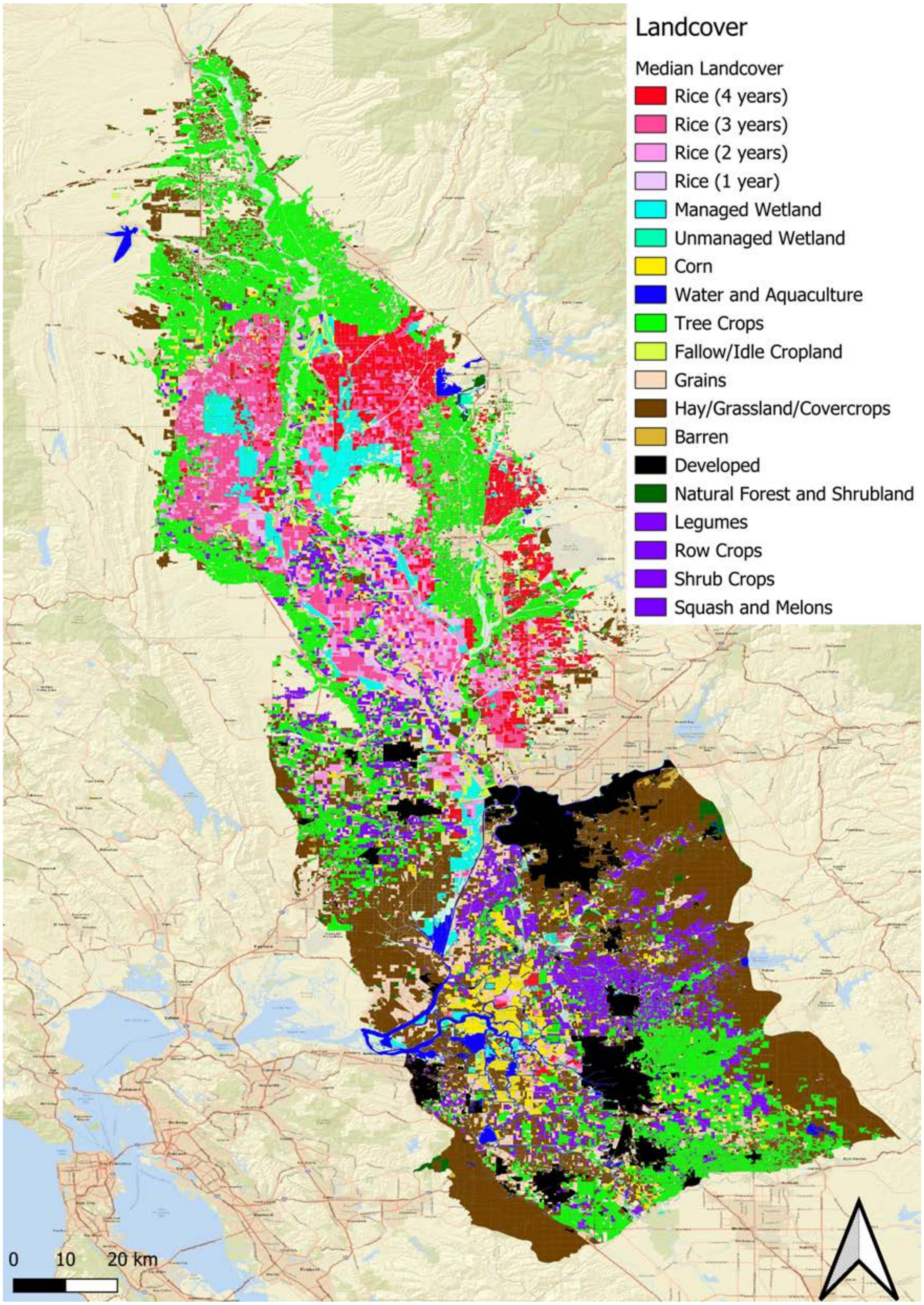


Figure 1. Consensus Landcover by Parcel for Rice Growing Region of Central Valley from 9/2020-3/2024

The habitat scenarios were developed using data from four recent years (2020/2021 to 2023/2024) to capture the variability in wetland and rice acreage, representing both favorable and unfavorable habitat conditions. These scenarios included years of high rice production with extensive wetland flooding, as well as years impacted by drought or reductions in rice acreage. In addition to the four years of data, we created a fifth scenario, 2223NR (No Rain), which represents an alternative outcome for 2022/2023. During that year, California experienced heavy drought, leading to reduced planting of agricultural land. However, substantial winter rains in early 2023 resulted in high flooding rates for the planted rice fields. The 2223NR scenario was constructed to model what would have occurred if the winter rains had followed the pattern of the other years, providing a consistent comparison across all scenarios. For this scenario, the January through March water data were replaced by taking the per-patch yearly average water chronology from the other years and multiplying by the December 2022 patch water coverage, constrained between 0 and 100% coverage.

For each year in the dataset, the habitat type for agricultural land was defined by the relevant Crop Data Layer (CDL) classification, with spatial majority filtering applied to reduce pixelation. While some habitat was classified as wetland in CDL, we also utilized additional data from the USGS, including high-resolution wetland maps from Audubon that provided conservation program information, management access, and habitat assessments with 89% accuracy. We also used a Ducks Unlimited map with similar quality but based on a slightly older data set, and a satellite-based raster from Point Blue that defined all managed wetland layers. Duck use data from USGS was further incorporated to refine the classification of these wetland habitats into used and unused wetlands. These different sources used varying methods to classify wetland habitats, and together they provided a comprehensive view of managed, unmanaged, and unused wetland areas.

For water coverage data, we used information from Patrick Donnelly's Wetland Evaluation Tool (WET) model. This wetland analysis product relies on satellite imagery to monitor the timing and duration of seasonal flooding on both natural and agricultural wetland habitats.

By defining scenarios that span typical and extreme conditions and incorporating detailed habitat data, we aimed to assess the resilience of duck populations in response to fluctuating habitat availability. This comprehensive approach ensures that the scenarios accurately reflect the range of conditions ducks may encounter during their wintering period, providing insights into how these changes can influence their survival and foraging success.

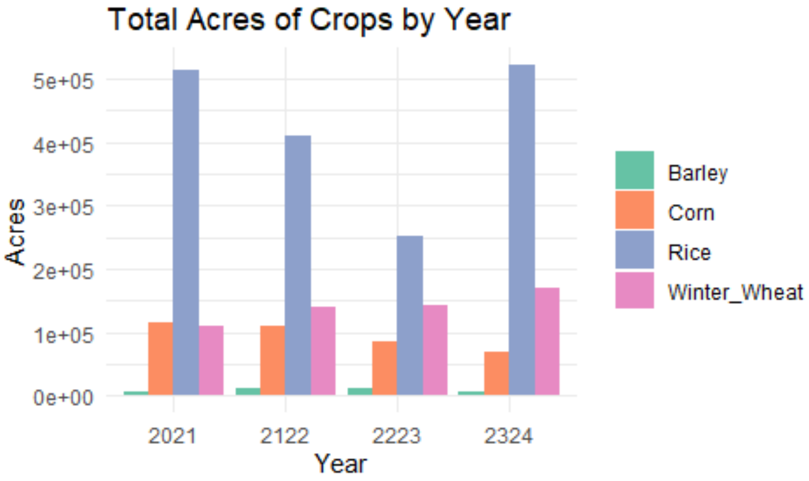


Figure 2. Total acres of four crops across the study region (from Chico to Modesto) for the 4 study years.

2.1.1 Habitat Scenarios

To better understand the habitat variability across different years, we considered several habitat scenarios.

Experiment 1 and 2 Habitat Scenarios In experiments 1 and 2, we used five distinct habitat scenarios representing data from four recent years (2020/2021 to 2023/2024) and an additional alternate scenario for 2022/2023 (2022/2023NR). These scenarios help us assess the relative quality of different years under varying goose foraging pressures and different population chronologies. Figure 2 below shows the total acres of crops across the study region for each of the four study years.

Notice that 20/21 and 23/24 are our good years, with over 500,000 acres of rice planted in the relevant area. 21/22 was marginal, with a bit over 400,000 acres planted, and 22/23 was a challenging year, with only about 250,000 acres of rice planted. For ducks, we are focused primarily on the wet acres of rice and corn crops, as well as wetland acres. We differentiate between managed and passive wetland acres in the model, and these habitats have different food values in the model. Below, in table 1, we list the total number of acres of each habitat type, as well as the maximum number of wet acres in any month for that scenario.

Table 1: Acres and max monthly wet acres by habitat and scenario.

Year	Rice Acres (Max Wet)	Corn Acres (Max Wet)	Managed Wetland Acres (Max Wet)	All Wetland Acres (Max Wet)
20/21	517,999 (270,384)	116,548 (17,706)	112,798 (95,463)	132,660 (106,249)
21/22	411,927 (228,205)	109,856 (13,468)	112,789 (99,660)	133,646 (112,392)
22/2	253,526 (219,631)	84,434 (19,214)	112,810 (108,613)	134,240 (126,962)
22/23NR	253,526 (131,883)	84,434 (7,120)	112,810 (90,018)	134,240 (101,105)
23/24	525,775 (285,835)	70,293 (9,688)	112,740 (99,616)	134,154 (112,734)

We can visualize this in Figure 3 below, which presents the acreage of wet rice fields and flooded managed wetland acreage by month for the five scenarios.

At peak, 20/21 and 23/24 had approximately 275,000 acres of wet rice in each, while 21/22 peaked around 225,000 acres. In 2223, the peak was also around 225,000 acres, but this peak was driven by late rain rather than planned winter flooding. The 22/23NR scenario was created to model conditions without the late rain, resulting in a peak flooded rice acreage of around 130,000 acres.

In all years without excessive winter rain, the wet managed wetland acreage ranged from 90,000 to 100,000 acres. This represents the planned flooding regimes. The 22/23 season peaked at 108,000 wet managed wetland acres, but this was driven mostly by rain, as the alternate rain scenario (22/23NR) actually had the least flooded acreage.

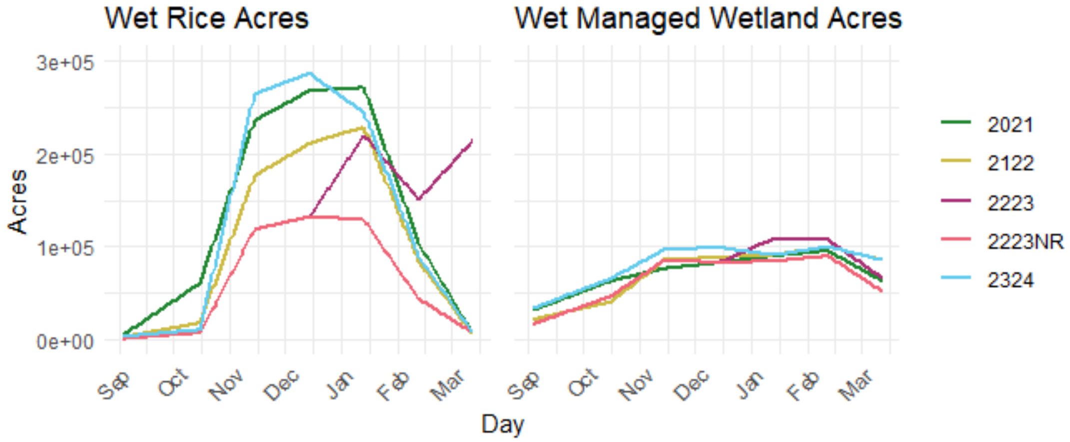


Figure 3. Winter Flooded Rice and Wet Managed Wetland Acreage by Scenario

The 23/24 season had the highest flooded wetland acreage of the scenarios without this heavy winter rain.

Experiment 3: Rice Acreage Scenarios: For experiment 3, we focused on determining the rice acreage threshold necessary to sustainable support the duck populations through winter. We developed 14 different rice acreage scenarios by incrementally adjusting the rice acreage from our baseline scenarios (either adjusting up or down from 21/22 or 23/24) to arrive at scenarios that spanned from 300,000 acres to 525,000 acres in 25,000 acres increments and included our 5 baseline scenarios. These scenarios are summarized in Table 2 below:

These scenarios allowed us to evaluate whether the amount of flooded rice in each of these settings was sufficient to sustain the duck population under two sets of conditions: 1. **Demanding Conditions** (Goose100 and SVDelayed treatments). 2. **Less-Demanding Conditions** (GooseScaled and SV treatments).

By assessing key metrics, we were able to estimate the minimum acreage necessary to maintain population health under both demanding and less-demanding competitive pressures and environmental conditions.

Building the Rice Acreage Scenarios To create the new acreage scenarios for Experiment 3, we started with the original habitat maps for the years 21/22 and 23/24, which provided distinct acreage values of rice from which to increase or reduce acreage. We then modified these scenarios by systematically adjusting the amount of rice in each scenario, while keeping other habitat factors, such as corn and wetland acreage, constant. To reduce the amount of rice, we first probabilistically removed acreage that was only rice habitat for one of the four years, then two, and so on until the total rice acreage in the new scenario matched the target rice acreage. Similarly, to add acres, we first probabilistically added patches that were classified as rice in three of the four years, then two, and so on. This approach allowed us to isolate the effect of rice acreage on the ability to sustain duck populations, without additional confounding from other habitat types.

These extended scenarios were crucial for understanding the threshold at which the availability of rice starts to provide sufficient energy for the wintering ducks, and when further increases in rice acreage bring diminishing returns in terms of population sustainability.

Table 2: Acres and max monthly wet acres by habitat and scenario.

Scenario	Rice Acres (Max Wet)	Scenario Description
254	253,526 (131,883)	Baseline from 22/23
254NR	253,526 (219,631)	Alternate Rain Scenario (22/23NR)
300	299,701 (178,633)	Experimentally Added Scenario (Reduced Acreage From 21/22)
325	324,678 (189,035)	Experimentally Added Scenario (Reduced Acreage From 21/22)
350	349,670 (200,635)	Experimentally Added Scenario (Reduced Acreage From 21/22)
375	374,756 (212,002)	Experimentally Added Scenario (Reduced Acreage From 21/22)
400	401,699 (222,539)	Experimentally Added Scenario (Reduced Acreage From 21/22)
412	411,927 (228,205)	Baseline from 21/22
425	426,148 (237,513)	Experimentally Added Scenario (Added Acreage From 21/22)
450	450,091 (244,099)	Experimentally Added Scenario (Added Acreage From 21/22)
475	475,266 (248,806)	Experimentally Added Scenario (Reduced Acreage From 232/4)
500	499,787 (257,727)	Experimentally Added Scenario (Reduced Acreage From 23/24)
518	517,999 (270,384)	Baseline from 2021
526	525,775 (285,835)	Baseline from 2324

2.2 Population Data and Chronology

The population data used in this study were drawn from several key sources, including the Midwinter Waterfowl Survey and the Sacramento refuge complex survey data and validated using observation data from the eBird platform. These data provided a comprehensive picture of duck population dynamics in the Central Valley, capturing population sizes and distribution patterns across multiple years. The Midwinter Waterfowl Survey, conducted annually, offers valuable insights into the abundance of waterfowl species at a critical time during their wintering period, while the refuge survey data provide additional spatial and temporal detail about duck use of specific wetland areas.

To construct population chronologies for the modeling effort, we used historical survey data to estimate the seasonal influx and outflux of ducks across the Central Valley. This included establishing typical arrival and departure timelines, as well as the peak population periods for each species using a generalized additive mixed model on the Sacramento Refuge Complex survey date from 2001-2018 (Fig 4). Adjustments were made to align these chronologies with the Central Valley Joint Venture (CVJV) population targets, which represent desired population levels to support long-term conservation goals. By aligning our chronologies with these targets, we ensured that our analysis not only reflected actual population trends but also provided insights into how current habitat availability measures up to conservation objectives.

The constructed chronologies were used to define the target duck populations, enabling us to evaluate whether the available habitat could sustain these populations under varying conditions.

Table 3: Mid-Winter Survey Waterfowl Species Counts by Region

	Count		
Species	Sacramento Valley	Yolo-Delta	Total
Am. Green-winged teal	200,401	51,413	251,814
Am. wigeon	178,346	87,259	265,605
Gadwall	69,020	4,206	73,226
Mallard	57,741	19,342	77,083
N. pintail	1,059,684	521,218	1,580,902
N. shoveler	253,065	163,013	416,078
Diving Ducks	96,549	99,124	195,673
TOTAL DUCKS	1,918,392	983,115	2,901,507

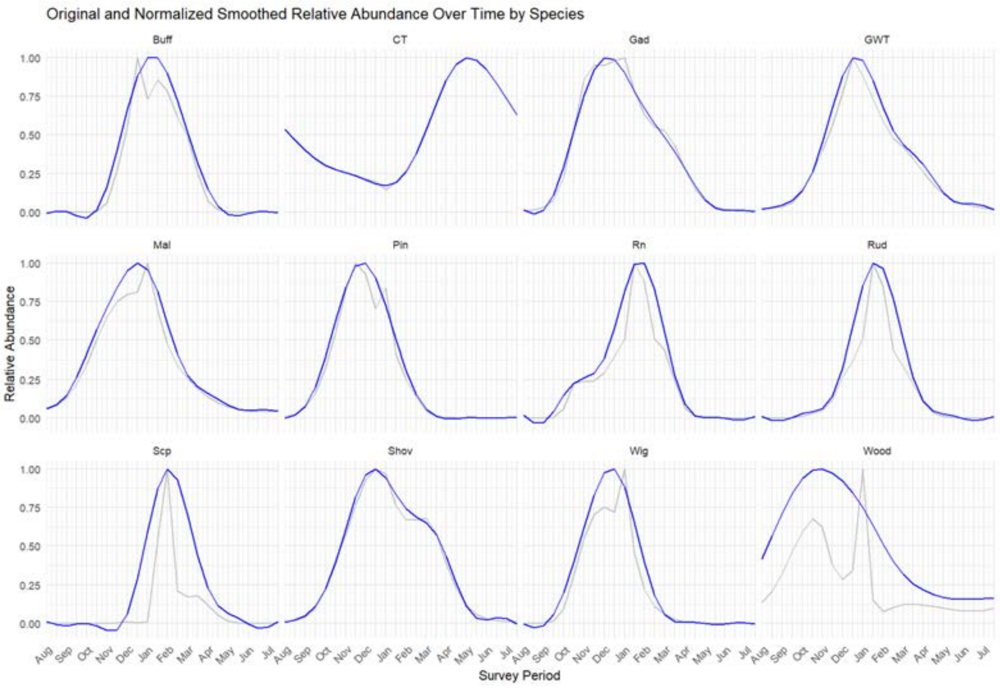


Figure 4. Original (grey) and smoothed (blue) relative abundance curves for each species from GAMM run on Sac Refuge survey data.

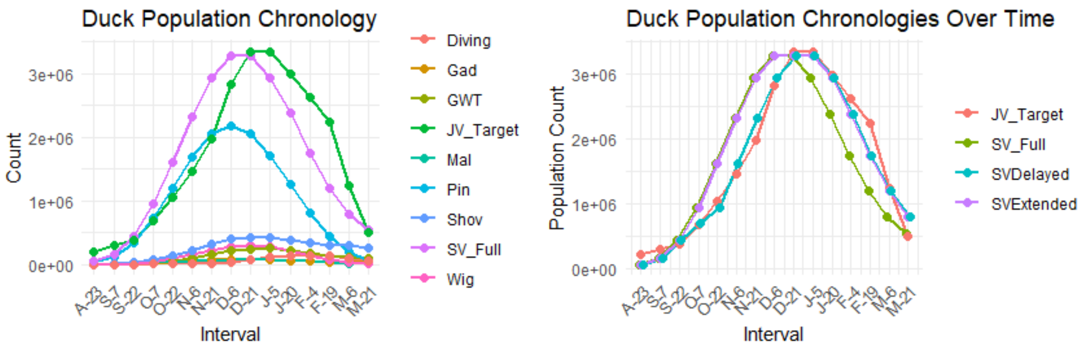


Figure 5. Alternative Target Duck Population Chronologies

Taken together, these combine to produce the following combined chronology (Figure 5). This is the extrapolated Sac Refuge Survey Chronology, and we'll denote it SV. The species-specific chronologies from this modeled chronology are also shown, as is the CVJV implementation plan target population. Notice that the JV target rises later and falls later than the SV chronology. To account for this, we've built two additional chronologies which we'll denote SVDelayed and SVExtended. In the SVDelayed chronology, we've pushed back each time point in the SV chronology from October 7 through March 21 by 15 days to try to match the general shape of the JVTarget chronology. In the SVExtended chronology, we've instead duplicated the December 21st point to January 5th and pushed the rest of the chronology back by 15 days. The SVExtended chronology should be the most difficult to provide enough food for as it has high early foraging pressure which remains high late in the season, and so we use it here to conservatively estimate the necessary rice acreage. These 4 alternative chronologies are shown in Figure 5.

2.3 Goose Competition Scenarios

Goose foraging was incorporated into the simulation using a MegaGoose agent, which represents the aggregated impact of all geese present in the study area. This agent removes food from the environment based on the total number of geese and their daily energy demand (DED). The DED and population estimate for geese were derived from the Central Valley Joint Venture (CVJV) implementation plan, ensuring that our modeling efforts were consistent with the established conservation goals and ecological understanding of the region.

The MegaGoose agent specifically targets energy resources in agricultural fields, particularly rice and corn. Once the energy available in these fields is exhausted, it is assumed that geese move on to other food sources, which reduces the pressure on ducks competing for the same resources. The simulation used three different goose foraging scenarios to examine the effects of varying levels of competition on duck populations:

1. **Goose100**: In this scenario, geese receive 100% of their energy from rice and corn fields. This represents the highest level of competition between geese and ducks for resources in agricultural habitats. The data for this scenario is shown in Figure 6 below.
2. **Goose75**: Here, geese obtain 75% of their energy from rice and corn fields, while the remaining 25% comes from other sources. This scenario simulates a moderate level of competition, providing a more balanced view of resource partitioning.

3. **GooseScaled**: In this scenario, the proportion of energy that geese receive from rice and corn fields is scaled based on their prevalence on the landscape compared to other crops, such as winter wheat and barley. This provides a dynamic and realistic representation of foraging pressure, which changes according to the available habitat.

The table below shows the rice and corn share for geese by year:

Table 4: Rice and Corn Share for Geese by Year

Year	Rice/Corn Share
2020-21	84.5%
2021-22	77.5%
2022-23	69.0%
2023-24	77.1%

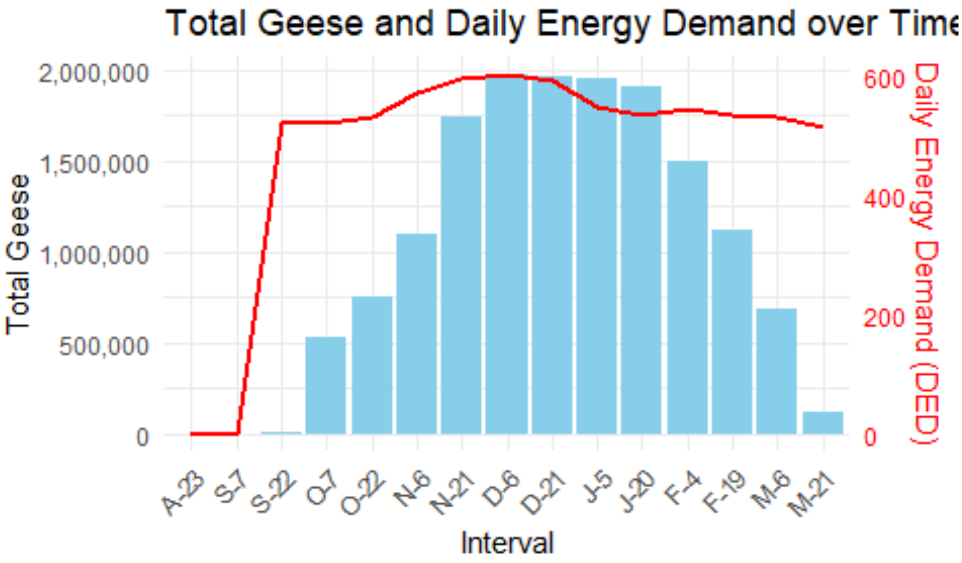


Figure 6. Goose Numbers and Daily Energy Demand for the Central Valley Waterfowl Foraging Model

2.4 Agent-Based Modeling Framework

The **Spatially-explicit Waterbird Agent-based Modeling Program (SWAMP)** forms the core of our agent-based modeling efforts, allowing us to simulate interactions between ducks, geese, and their habitats in the Central Valley of California. The detailed description of SWAMP, its purpose, and its primary components has already been provided in earlier sections. In this section, we summarize how SWAMP was adapted to address the specific needs of this study, including the incorporation of the **MegaGoose agent** to simulate competition for resources between ducks and geese.

2.4.1 Overview of Model Components

- **Duck Agents**: As described earlier, SWAMP models individual ducks as agents with behaviors governed by energy-maximizing rules. Ducks move across the landscape, foraging for food in wetland and agricultural habitats based on the availability of resources, the presence of competitors, and other environmental factors.

- **MegaGoose Agent**: Goose foraging was incorporated into the model through the MegaGoose agent, representing an aggregate of all geese in the study area. The MegaGoose agent consumes food resources from agricultural fields (primarily rice and corn) based on the **Daily Energy Demand (DED)** and population estimates of geese, which were derived from the Central Valley Joint Venture (CVJV) implementation plan. The scenarios explored in this study include variations in goose foraging behavior (e.g., Goose100, Goose75, GooseScaled) to assess how different levels of interspecies competition influence duck energetics and habitat use.

2.4.2 Spatially-Explicit Landscape

The spatial extent of the model includes the rice-growing regions of the Central Valley, from Red Bluff to Stockton, with a focus on six primary basins: **Colusa, Butte, American, Sutter, Yolo**, and **Delta**. The landscape is represented using GIS data, allowing for the **spatially-explicit simulation** of foraging activities across wetlands and agricultural fields, as previously outlined in the "Study Area and Scenario Generation" section.

2.4.3 Agent Behavior and Model Dynamics

The behavior of duck agents, including **foraging, patch selection, and energy dynamics**, is modeled based on empirical data and known ecological behaviors. As described previously, the model uses a **type II functional response** to simulate food acquisition and incorporates rules for foraging and refuge-seeking behavior throughout each model day. GIS tracking data was used to designate patches as available roosts in the landscape map. The inclusion of competition scenarios with the MegaGoose agent provides insight into how interspecies interactions affect habitat use and overall carrying capacity.

2.4.4 Duck Roosting Sites

To accurately model duck movement and behavior within the Central Valley landscape, it was crucial to identify key roosting sites used by wintering waterfowl. Roosting sites were determined using GPS telemetry from tagged and tracked waterfowl, provided by USGS. These tracked locations offered insights into the spatial preferences of waterfowl, and our approach aimed to identify the most significant areas.

A roosting location was defined based on the following criteria:

1. **Movement Distance**: A sequence of GIS locations was identified as a potential roosting site if the movement between successive locations was within 60 meters. This criterion ensures that the birds were largely stationary, indicative of roosting rather than foraging or flight behavior.

2. **Duration**: The sequence of movements within the 60-meter threshold had to las for at least three consecutive hours. This duration requirement helped to differentiate between brief pauses in movement and genuine roosting behavior.

3. **Number of Locations**: Each roosting sequence had to include more than three GPS points, with longer intervals required for GPS data recorded at less frequent than hourly intervals. This criterion further ensured that the identified locations were consistently used by the ducks for extended periods.

4. **Time of Year**: Potential roosting locations were filtered to those that occurred between September and March, both to match our simulation time frame, but also to exclude molting or brooding behavior.

The 810,243 roosting events are shown in Figure 7 below.

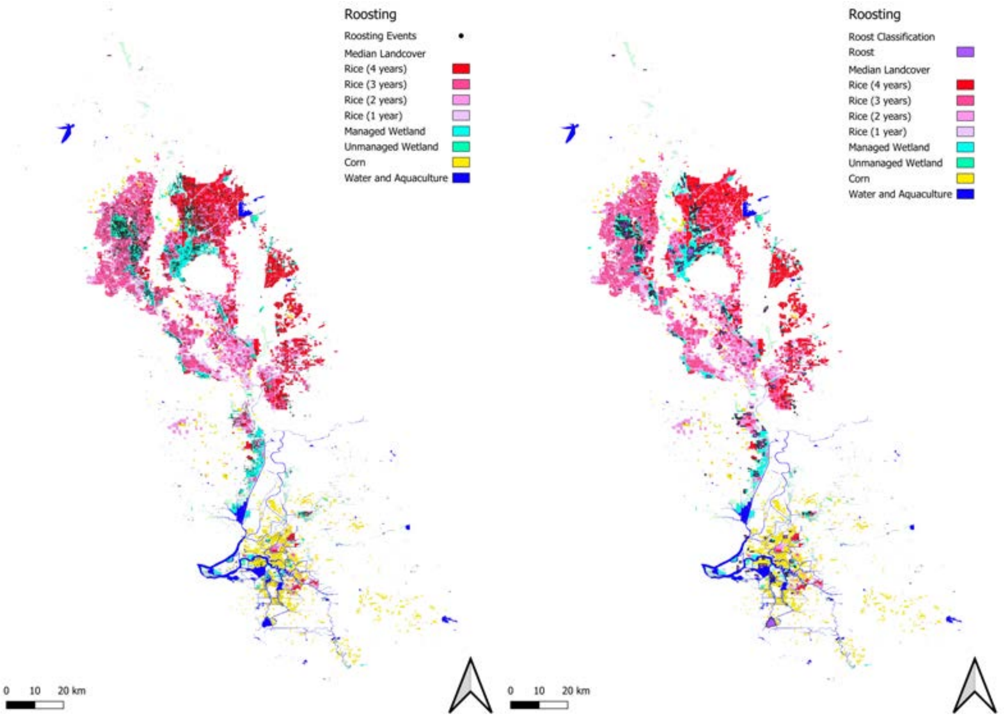


Figure 7. A) All individual Roosting Events and B) Chosen Roost Polygons.

Once individual roosting locations were identified, these points were aggregated into the polygons in our map layer. This aggregation allowed us to analyze at the larger spatial scale of our map rather than focus on individual GPS points, providing a more realistic representation of roosting habitats.

Roost Site Selection: Polygons were evaluated using a composite metric designed to capture the relative importance of each roosting site within the landscape. This metric was based on the following factors:

1. **Number of Roostings (N)**: The total number of roosting events observed within a given polygon.

2. **Roosting Density (N/A)**: The density of roosting events, calculated as the number of roostings (N) divided by the area of the polygon (A). This metric provided a measure of how intensively each roosting area was used.

3. **Basin Adjustment (N/B)**: An adjustment for basin-level use, calculated as the proportion of total roostings within a basin that occurred within the polygon (N/B). This allowed us to account for regional variation in roosting activity across different basins in the study area.

The final metric used to select roost sites was calculated as **N x (N/A) X (N/B)**. This combined metric ensured that we prioritized roosting sites with high use, high density, and significant regional importance. Based on this composite metric, the top 500 polygons were selected as roost sites for use in the agent-based model.

Roost Site Characteristics: These 500 roosting sites accounted for 544,621 of the 810,243 individual roosting points (67.2%) within the dataset, despite accounting for only 5% of the total map area. The habitat composition of the selected roost sites included wetlands (61.4% of total roost area occurred in wetland habitats), rice fields (22.7%), corn fields (4.5%) and other habitat types (11.4%, includes pasture, other agriculture, riparian areas, etc.).

Most of the roost polygons were located in or around wildlife refuge areas or large contiguous areas of managed wetlands, including prominent sites such as the Sacramento National Wildlife Refuge, Delevan National Wildlife Refuge, Colusa National Wildlife Refuge, Grey Lodge Wildlife Area, Butte Sink Wildlife Management Area, Sutter National Wildlife Refuge, Yolo Bypass Wildlife Area, and Cosumnes River Preserve. These findings underscore the importance of maintaining and managing these key habitats for sustaining waterfowl populations during the winter season.

This identification of roosting sites played a critical role in defining key resting and staging areas for ducks in our agent-based model, thereby providing a realistic spatial context for simulating their energy balance, movement, and foraging behaviors across the winter landscape.

2.4.5 Model Assumptions and Scenarios

To evaluate the impact of landscape changes and competition on habitat sufficiency, SWAMP was used to simulate multiple scenarios:

1. **Habitat Scenarios**: Scenarios representing different habitat conditions (e.g., annual variations in rice and wetland acreage) were developed based on data from four recent years, as outlined in the “Habitat Scenarios” section.

2. **Goose Competition Scenarios**: Goose foraging scenarios (Goose100, Goose75, GooseScaled) provided insight into how varying levels of competition influenced duck foraging success and energy balance, particularly under conditions of limited food availability.

3. **Rice Acreage Scenarios**: In addition to the five scenarios built from our four years of habitat and water data, we explore waterfowl population performance on a range of rice acreage scenarios spanning from 254,000 acres to 526,000 acres of rice.

2.4.6 Key Advantages of the Agent-Based Modeling Approach

Compared to traditional **duck energy-day (DED)** models, SWAMP offers several key advantages, including:

- The ability to **model individual variability** among waterfowl, capturing the effects of landscape heterogeneity on foraging behavior and energy dynamics.
- **Spatially-explicit predictions** of foraging success, which are critical for evaluating the effectiveness of habitat management actions.
- The capacity to simulate the **combined effects of multiple factors**, such as habitat availability, competition, and environmental conditions, providing a more comprehensive assessment of habitat sustainability for waterfowl.

These advantages make SWAMP a powerful decision-support tool for conservation planning, enabling stakeholders to explore the impacts of different management actions and identify strategies that promote habitat sustainability and population resilience.

2.5 Simulation Design and Data Analysis

The SWAMP model was used to conduct two sets of experiments, each focusing on different aspects of habitat sustainability for ducks in the Central Valley:

2.5.1 Experimental Design

Experiment 1: Effect of Goose Treatment on Habitat Scenarios

In the first set of simulations, we assessed the impact of goose foraging pressure across five different habitat scenarios representing landscape variations from recent years. The habitat scenarios included the four years from 2020/2021 to 2023/2024, plus an alternative scenario for 2022/2023 with modified winter rain conditions (22/23NR). Each scenario was run with three different goose treatments: Goose100, Goose75, and GooseScaled, providing a comprehensive look at how different levels of interspecies competition influence duck habitat use, energy dynamics, and survival.

For each treatment-scenario combination, the model was run for ten replicates each spanning 195 days, from September 1 to mid-March. The goal of this experiment was to determine how variation in goose foraging pressure affected habitat sufficiency across a range of habitat conditions, from favorable (e.g., high rice acreage) to challenging (e.g., low rice acreage and drought conditions).

Experiment 2: Effect of Population Chronology on a Median Landscape Scenario

The second set of experiments focused on the effect of different population chronologies within a single habitat scenario. We selected 2122 as a representative median scenario, and it also exhibited a high sensitivity to changes in foraging pressure during preliminary analyses. In this experiment, the goose treatment was fixed at Goose100, and different population chronologies were simulated: SV (Sacramento Valley extrapolated), SVDelayed, SVExtended, and JVTarget. These chronologies reflect variations in the timing and abundance of duck arrivals, representing different potential population dynamics. The goal was to evaluate how variations in the timing and abundance of duck arrivals affected overall habitat sufficiency and population outcomes. Similar to Experiment 1, simulations were run from September 1 to mid-March.

Experiment 3: Determining the Rice Acreage Threshold for Sustainable Duck Populations

In the third set of simulations, we sought to identify the minimum flooded rice acreage required to sustainable support wintering duck populations under varying competitive and environmental conditions. To achieve this, we generated 14 different rice acreage scenarios, ranging from 254,000 to 526,000 rice acres, under two sets of conditions:

1. **Demanding Conditions**: These conditions applied Goose100 and SVDelayed treatments to simulate challenging conditions for the ducks. This represents high competition for food resources and a population chronology that pressures the landscape late in the winter when food becomes scarcer.

2. **Less-Demanding Conditions**: For these conditions we used GooseScaled and SV treatments to simulate more favorable conditions. This scenario involved a lower level of interspecies competition and a chronology that pressures the landscape earlier in the season when food is more abundant.

We ran five replicates of each rice acreage scenario, resulting in a comprehensive assessment of how different rice acreage levels impacted duck energetics, population health, and overall habitat sufficiency.

This experiment allowed us to identify the threshold rice acreage needed to maintain sufficient energy resources and population health under both challenging and less-demanding conditions. By comparing the key metrics under these two different treatments, we defined GREEN, YELLOW, and RED rice acreage scenarios, indicating the levels at which habitat sufficiency could be reliably achieved, partially achieved, or not achieved. This information provides key insights for habitat management, particularly considering fluctuating water availability and rice acreage.

2.5.2 Simulation Outputs

The following metrics were tracked during the simulations to assess habitat sustainability for ducks and to evaluate how different landscape and competition scenarios influenced outcomes:

- **Population Size and Emigration/Survival Rates**: We tracked the population size over the course of each simulation, as well as the percentage of the target population that survived. This metric also included the emigration rate of ducks that were unable to meet their energetic needs and left the study area, providing insight into the impact of different habitat conditions and goose foraging pressures on population success.

- **Landscape Energy Availability**: The total available energy in the landscape was recorded throughout the simulation period, with special focus on energy availability within 5 km of roost sites. This metric helped to determine how accessible food resources were for foraging ducks, which is crucial for understanding the spatial limitations of habitat suitability.

- **Average Daily Net Energy**: This metric was built from the average daily intake and daily energy demand of ducks, providing a measure of energy balance. A positive net energy value indicates sufficient food intake, while negative values suggest a potential energy deficit, which could lead to reduced body condition or increased mortality. The day at which the energy balance flips to negative is Days to Deficit (DTD) and can be used to compare relative habitat suitability.

- **Duck Lipid Levels**: The percent of lipid capacity (i.e., body fat reserves) was tracked for each duck throughout the simulation. Lipid reserves are critical for ducks to endure periods of food scarcity and for preparation for spring migration. Declining lipid levels can indicate poor habitat conditions or high competition pressure.

- **Energy Demand Days Remaining (EDDR)**: This metric represents the number of days of energy available based on the current energy supply and daily demand. It provides a way to estimate how long the current landscape can sustain the population under different foraging pressures, serving as a key indicator for identifying periods of critical resource shortages.

- **Earliest Expected Energy Depletion Day (EEEDD)**: This metric represents the earliest day within the season that food energy could be expected to be depleted. Each day, we take the EDDR and add it to the day to project what day energy would be depleted based on current energy demand. EEEDD is the minimum of these projections.

- **Diet Composition**: The proportion of the diet consisting of moist soil seeds, rice, and invertebrates was calculated for the duck populations. Changes in diet composition can provide insights into how ducks are adapting to resource limitations and competition, and whether they are forced to rely on less-preferred food sources.

- **Average Foraging Flight Distances and Exploitation Index**: The average distance traveled by ducks during foraging flights was recorded to evaluate the spatial effort required to find food. Additionally, an **Exploitation Index** was calculated to represent the relative food availability in the vicinity of roosts, helping to understand the impact of spatially localized resource depletion on foraging behavior.

2.6 Key Metrics and Indicators

To determine the acreage of winter rice required to sustain healthy duck populations in the Central Valley, we defined specific metrics that characterize a “healthy population.” These metrics include:

Population Size Thresholds

- **Target Population Maintenance**: A healthy population is defined as maintaining at least **50% of the target population** until late in the season. This threshold ensures that the population can withstand temporary periods of low resource availability and persist in significant numbers.

- **Population at Day 150**: By the beginning of February (approximately day 150 of the simulation), when alternative habitats may become available to the north, the population should be **above 90% of the target**. This metric indicates that the population is in good condition and able to capitalize on emerging habitat opportunities.

Emigration and Biomass Export

- **Emigration Timing and Lipid Levels**: Ducks that emigrate from the landscape later in the season and with higher lipid reserves indicate a healthier population. High lipid levels suggest that individuals have had sufficient access to food resources to meet their energy demands and prepare for migration. We use an **aggregate metric of emigrant timing and lipid levels** to evaluate the overall success of the population in maintaining adequate energy reserves throughout the season.

Total Duck Use Days

- **Duck Use Days**: This metric represents the cumulative number of days that ducks utilize the habitat during the non-breeding season. We establish a threshold number of duck use days necessary to classify the population as healthy, providing an overall measure of habitat utility and sustainability.

Days To Deficit (DTD)

- Ducks must maintain a **positive average daily net energy** until late in the season to sustain their body condition and survival. The Days to Deficit metric indicates at what date the average duck's net energy balance becomes negative, and a DTD greater than 150 (early-February), combined with lipid levels above a certain threshold capacity suggests that individuals in the population can safely survive until migration

Earliest Expected Energy Depletion Day (EEEDD)

- **EEEDD** is calculated as the minimum of the sum of EDDR+day, indicating the earliest day on which landscape energy is projected to be depleted. A higher EEEDD value is indicative of a more resilient habitat capable of supporting the population in the face of environmental variability.

These key metrics collectively provide a comprehensive understanding of the population's health and the habitat's suitability. By using these indicators, we can determine the minimum rice acreage needed to support a healthy duck population, providing valuable insights for conservation planning and management decisions.

3. Simulation Results

3.1 Overview of Simulation Scenarios and Experimental Design

The simulations were designed to assess the impact of habitat variability, interspecific competition, and different population chronologies on the sustainability of duck populations in California's Central Valley. To achieve this, we conducted three sets of experiments using a combination of habitat scenarios, goose foraging pressure treatments, and duck population chronologies. This approach allowed us to explore how fluctuating habitat availability, competition for resources, and different population arrival patterns influenced duck energetics and population health over a typical winter season.

- **Habitat Scenarios**: The habitat scenarios were based on data from four recent years (2020/2021, 2021/2022, 2022/2023, and 2023/2024) and included an additional scenario

(2223NR) that modeled an alternate outcome for 2022/2023, excluding the impact of heavy winter rains. Each scenario provided a unique set of habitat conditions, ranging from favorable (high rice and wetland acreage, 2020/2021 and 2023/2024) to challenging (low rice acreage and drought conditions, 2022/2023).

- **Goose Foraging Scenarios**: We simulated three levels of goose foraging pressure to understand the effects of interspecific competition:
    - **Goose100**: Geese obtained 100% of their energy from rice and corn fields, representing the highest level of competition between geese and ducks.
    - **Goose75**: Geese received 75% of their energy from rice and corn fields, with the remaining 25% from other sources, providing a moderate level of competition.
    - **GooseScaled**: The proportion of energy geese obtained from rice and corn fields was dynamically scaled based on their prevalence on the landscape, simulating a realistic, context-dependent level of competition.
- **Population Chronologies**: We used multiple population chronologies to assess the effect of different timing and abundance of duck arrivals:
    - **SV**: The base population chronology derived from survey data, representing typical arrival and departure patterns.
    - **SVDelayed**: A delayed version of the SV chronology, where the arrival and departure timings were pushed back by 15 days.
    - **SVExtended**: An extended version of the SV chronology, with higher early foraging pressure and extended presence, representing the most challenging scenario for habitat sufficiency.
- **Key Objectives of Each Experiment**:
    - **Experiment 1**: Determine how different levels of goose foraging pressure impacted duck population sustainability across the five habitat scenarios, focusing on how interspecies competition influenced duck energetics, survival, and foraging behavior.
    - **Experiment 2**: Assess the impact of different population chronologies on a median landscape scenario (2122) to determine how variations in the timing and abundance of duck populations affected habitat sufficiency.
    - **Experiment 3:** Determine the minimum rice acreage needed to sustain wintering duck populations by simulating a range of rice acreage scenarios, from 254,000 to 526,000 acres, under both demanding (Goose100 and SVDelayed) and less-demanding (GooseScaled and SV) conditions. This experiment aimed to identify the acreage thresholds necessary for maintaining population health under varying competitive and environmental conditions.

Together, these experiments provided a comprehensive understanding of how habitat availability, competition, and population dynamics influence the ability of the Central Valley to sustain wintering duck populations. The insights gained from these simulations are crucial for informing adaptive management strategies, particularly in light of increasing variability in water availability, to ensure long-term resilience of waterfowl habitats.

3.2 Experiment 1: Goose Foraging Levels

3.2.1 Population Size and Emigration Patterns

The response of duck populations to different goose foraging scenarios varied significantly across the five habitat conditions simulated. The results demonstrate how goose competition levels directly influenced population dynamics, particularly in challenging habitat years.

Duck Population vs. Target Population

Figure 8 presents duck population versus target by date for each of the five habitat scenarios, paneled by goose treatment (Goose100, Goose75, GooseScaled). The figure shows that favorable habitat years (2021 and 2324) were able to support the population close to the target until late in the season, whereas challenging years (2223 and 2223NR) saw earlier declines. The Goose75 and GooseScaled treatments allowed populations to persist longer compared to Goose100.

In favorable years like 2021 and 2324, the duck population was sustained near the target throughout most of the season. However, challenging years such as 2223 and 2223NR experienced significant declines, particularly under the Goose100 scenario. Goose75 and GooseScaled treatments provided a buffer, delaying population declines and extending viability, especially in challenging conditions.

Table 5. Percent of target population on day 150 (Feb. 1). We consider a population >90% of target on this day to be meeting expectations.

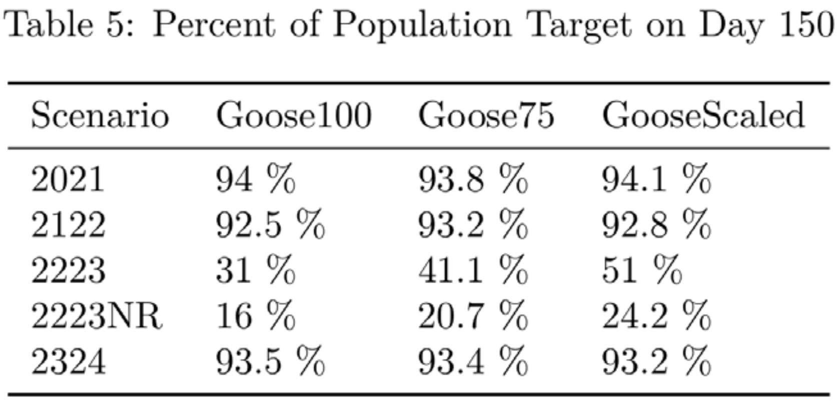


Table 5: Percent of Population Target on Day 150

Scenario	Goose100	Goose75	GooseScaled
2021	94 %	93.8 %	94.1 %
2122	92.5 %	93.2 %	92.8 %
2223	31 %	41.1 %	51 %
2223NR	16 %	20.7 %	24.2 %
2324	93.5 %	93.4 %	93.2 %

Table 6. Total duck use days over the season for each scenario, and the percentage of the target duck use days attained based on the SVExtended Chronology.

Table 6: Percent of Target Total Duck Use Days by Scenario

Scenario	Goose100	Goose75	GooseScaled
2021	96.4 %	97.2 %	97.1 %
2122	93.6 %	95.6 %	95.7 %
2223	75.5 %	80.3 %	82.1 %
2223NR	68 %	72.6 %	74.7 %
2324	96.6 %	97.2 %	97 %

Population Decline Analysis

Figure 8 displays duck population as a percentage of the target by date for each of the five scenarios, highlighting when populations drop and by how much relative to the target. Goose75 and GooseScaled scenarios delayed population declines by up to a week or more compared to Goose100.

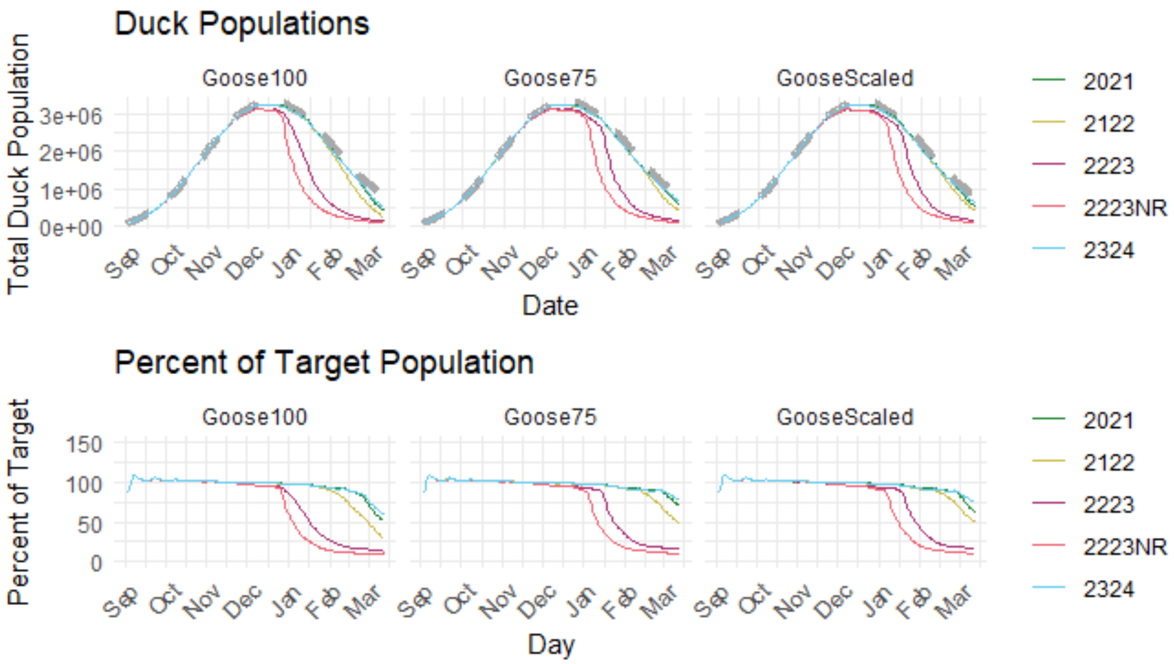
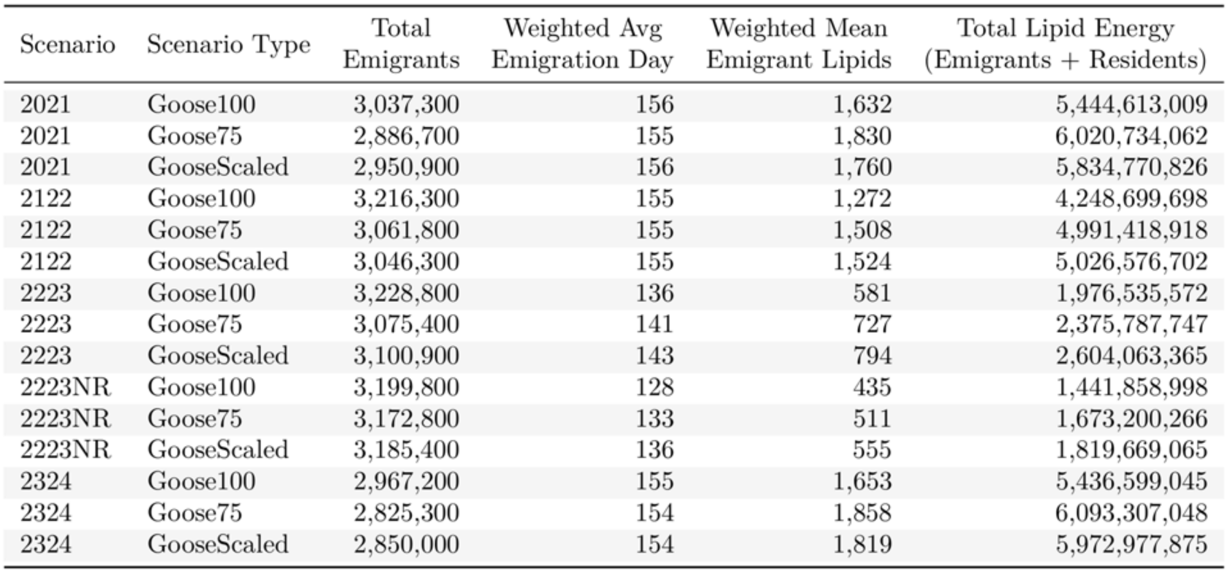


Figure 8. Duck Population and Percent of Target Population by Date for Five Habitat Scenarios.

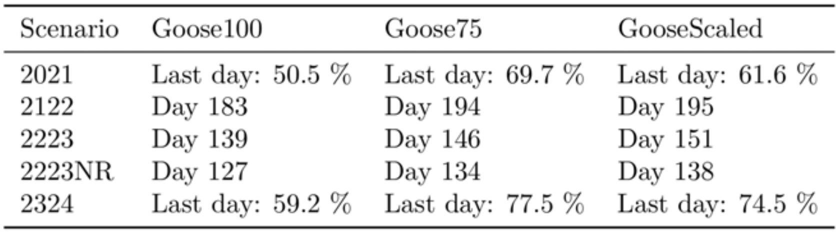
Table 7: Aggregate Metrics of Emigrant Timing and Lipid Levels by Scenario



Scenario	Scenario Type	Total Emigrants	Weighted Avg Emigration Day	Weighted Mean Emigrant Lipids	Total Lipid Energy (Emigrants + Residents)
2021	Goose100	3,037,300	156	1,632	5,444,613,009
2021	Goose75	2,886,700	155	1,830	6,020,734,062
2021	GooseScaled	2,950,900	156	1,760	5,834,770,826
2122	Goose100	3,216,300	155	1,272	4,248,699,698
2122	Goose75	3,061,800	155	1,508	4,991,418,918
2122	GooseScaled	3,046,300	155	1,524	5,026,576,702
2223	Goose100	3,228,800	136	581	1,976,535,572
2223	Goose75	3,075,400	141	727	2,375,787,747
2223	GooseScaled	3,100,900	143	794	2,604,063,365
2223NR	Goose100	3,199,800	128	435	1,441,858,998
2223NR	Goose75	3,172,800	133	511	1,673,200,266
2223NR	GooseScaled	3,185,400	136	555	1,819,669,065
2324	Goose100	2,967,200	155	1,653	5,436,599,045
2324	Goose75	2,825,300	154	1,858	6,093,307,048
2324	GooseScaled	2,850,000	154	1,819	5,972,977,875

Table 8 summarizes the day on which the population first fell below 50% of the target, or, if the population never dropped below 50%, the percentage of the target on the last simulation day. This table provides a clear comparison of the timing and extent of population declines across scenarios.

Table 8: Day on Which Population Falls Below 50 Percent of Target, OR Percent of Target on Day 195



Scenario	Goose100	Goose75	GooseScaled
2021	Last day: 50.5 %	Last day: 69.7 %	Last day: 61.6 %
2122	Day 183	Day 194	Day 195
2223	Day 139	Day 146	Day 151
2223NR	Day 127	Day 134	Day 138
2324	Last day: 59.2 %	Last day: 77.5 %	Last day: 74.5 %

The table and figure together show that reducing goose competition through Goose75 or GooseScaled treatments can significantly delay the point at which duck populations fall below critical thresholds. In scenarios like 2223, these treatments extended population viability by up to two weeks, which is crucial for ensuring survival during critical periods of the winter season. Relative to our target population, the 2021 and 2324 duck populations perform well in all scenarios, maintaining their population at or near target until late in the season even in the Goose100 scenario, though the populations do begin to decline below target around day 175 and dip to approximately 50% by day 195. This dip is somewhat less pronounced in the GooseScaled scenario, and much less pronounced in the Goose75 scenario, where populations are still at ~75% on day 195.

The 22/23 scenarios are always fairly catastrophic, and the changes in goose scenario only affect which day the crash comes. Notably, the 2223 late rains make a significant difference, delaying the crash by ~12 days relative to 2223NR.

The 21/22 scenario is the most sensitive to scenario, suggesting it is near our acreage minimum target. going from Goose100 to GooseScaled or Goose75 give this scenario an additional 10-11 days before crashing to 50% and pushes much closer to remaining at or above 50% by day 195 (mid-March).

3.2.2 Landscape Energy Availability

Energy Availability in the Landscape

Figure 9 shows landscape energy availability by day for each scenario (both for the full landscape and within a 5km radius), paneled by goose treatment. Energy peaks around mid-November before declining due to foraging and other factors. Invertebrate availability comes online in January (day 120), causing a bump in available energy. The late rain in the 2223 scenario provided a noticeable boost compared to 2223NR.

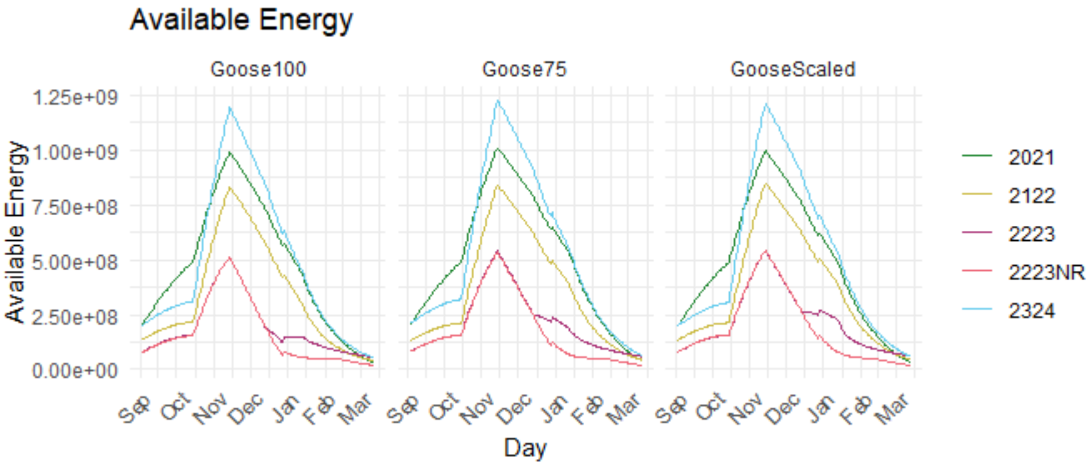


Figure 9. Landscape Available Energy by Date for Five Habitat Scenarios.

Energy availability peaked in mid-November across all scenarios, but the subsequent decline was more pronounced in challenging years like 2223NR. The late rain in 2223 provided a temporary boost, delaying energy shortages. Goose75 and GooseScaled treatments helped maintain higher energy availability for a longer period, particularly within the critical 5km radius of roost sites.

Notice that the actual differences between scenarios are relatively small, but these small differences at peak, for example, end up having relatively larger impacts later in the season.

Goose and Duck Energy Removal

Goose energy removal consistently exceeded that of ducks (Figure 10), especially in the Goose100 scenario. This highlights the significant impact of interspecies competition on resource availability, which in turn affects duck survival and energetics.

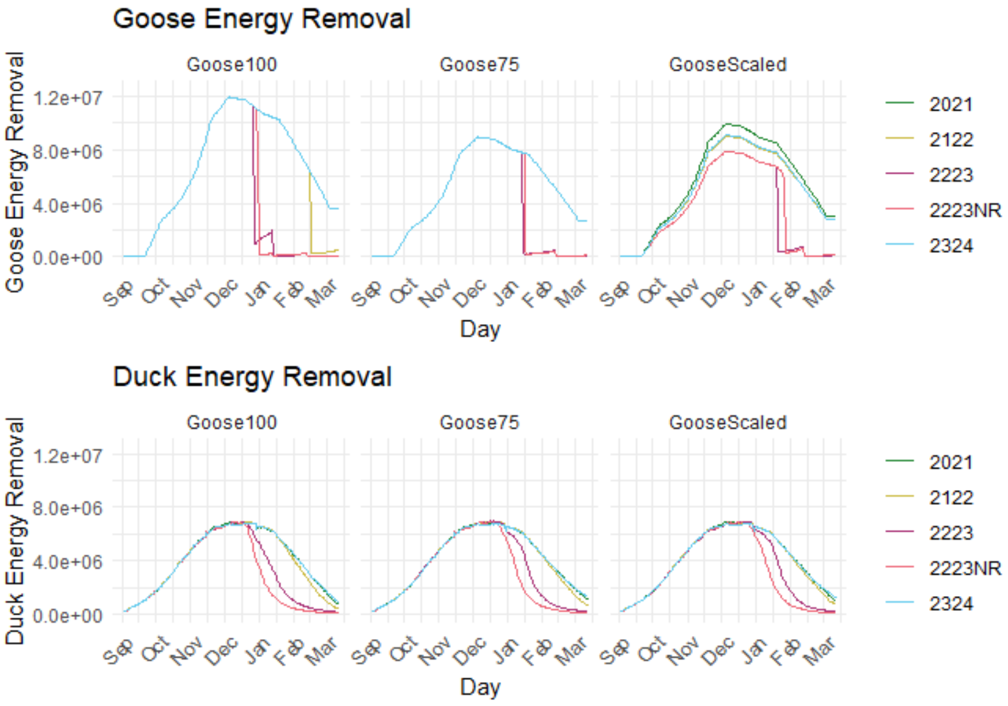


Figure 10. Energy removal by geese and ducks across scenarios

3.2.3 Duck Energetics and Energy Balance

Daily Net Energy Balance

Figure 11 shows average daily net energy by day for each scenario, paneled by goose treatment. Energy balance is maintained early in the season but begins to diverge across scenarios in late December.

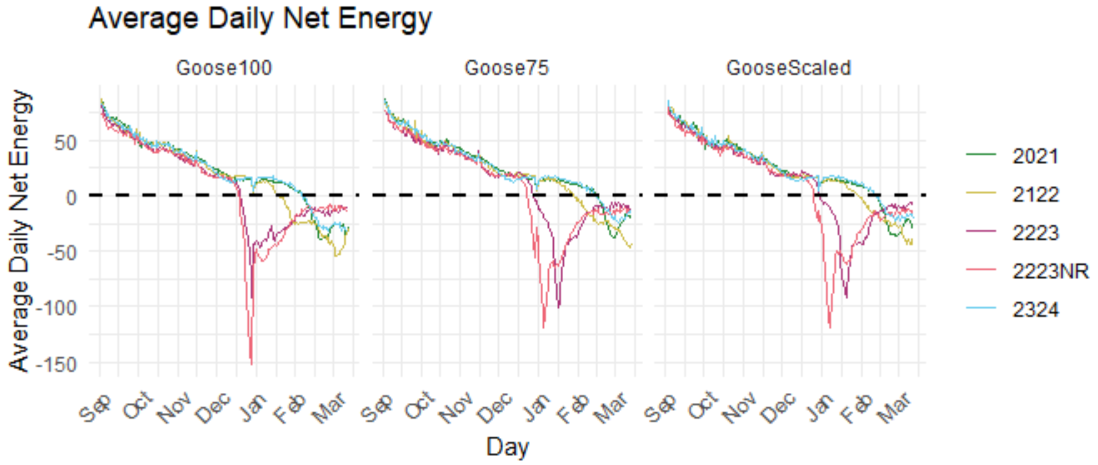


Figure 11. Duck Energy Balance by Date for Five Habitat Scenarios.

Table 9 summarizes Days to Deficit (DTD) for each scenario and goose treatment, indicating when ducks begin to experience negative energy balance.

Table 9: Days to Deficit (DTD) by Scenario

Scenario	Goose100	Goose75	GooseScaled
2021	Day 160	Day 169	Day 167
2122	Day 142	Day 151	Day 152
2223	Day 112	Day 120	Day 122
2223NR	Day 110	Day 115	Day 117
2324	Day 160	Day 169	Day 166

Goose75 and GooseScaled treatments delayed the onset of negative energy balance compared to Goose100, especially in favorable habitat years (2021, 2324). In challenging years, ducks under Goose100 experienced negative energy balance earlier, leading to declines in body condition and increased risk of mortality or emigration.

Duck Lipid Levels

Figure 12 shows lipid levels and the proportion of lipid capacity filled by day for each scenario. The figure highlights divergence from favorable conditions, with challenging years like 2223 showing earlier and more severe declines.

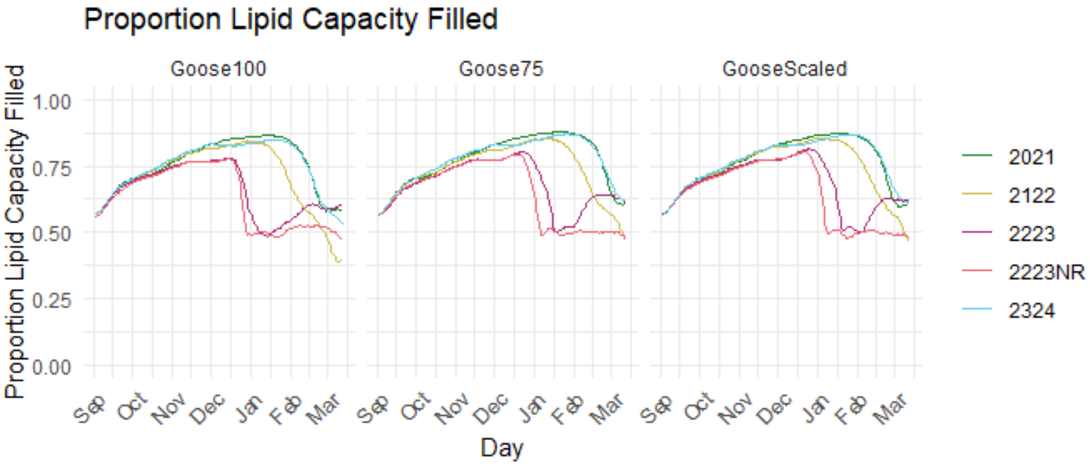


Figure 12. Duck Lipid Levels by Date for Five Habitat Scenarios.

Ducks in favorable scenarios (2021, 2324) were able to build and maintain lipid reserves until late in the season, whereas challenging scenarios (2223, 2223NR) showed earlier declines in lipid levels. Goose75 and GooseScaled treatments helped ducks maintain higher lipid reserves, reducing the likelihood of mortality during critical periods.

3.2.4 Foraging and Habitat Use Patterns

Energy Demand Days Remaining (EDDR)

Figure 13 presents EDDR by day for each scenario, indicating when resource shortages were most critical.

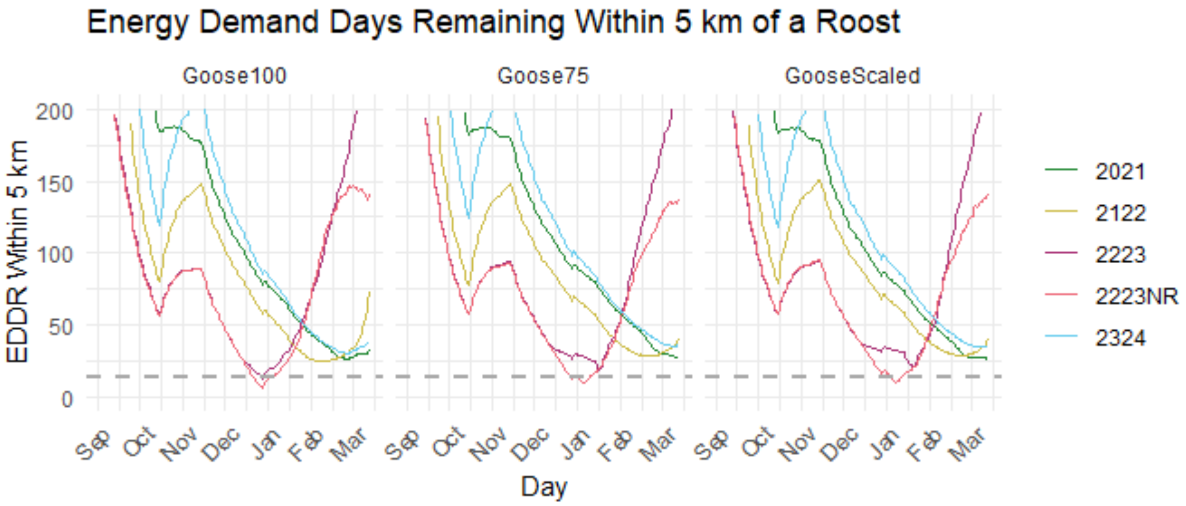


Figure 13. Duck Energy Demand Days Remaining by Date for Five Habitat Scenarios.

Table 10 summarizes the date and level of the EDDR minimum for each scenario and goose treatment.

Table 10: Minimum Energy Demand Days Remaining Day and Level

Scenario	Goose100	Goose75	GooseScaled
2021	Day 179 - Min: 26.6	Day 194 - Min: 27.1	Day 194 - Min: 26.8
2122	Day 160 - Min: 24.8	Day 174 - Min: 28.3	Day 177 - Min: 28.4
2223	Day 119 - Min: 12.8	Day 138 - Min: 18.9	Day 142 - Min: 20.9
2223NR	Day 119 - Min: 5.9	Day 127 - Min: 9.8	Day 129 - Min: 10.6
2324	Day 179 - Min: 30.4	Day 190 - Min: 35.5	Day 189 - Min: 34.5

The EDDR analysis shows that Goose75 and GooseScaled treatments delayed the point of critical resource shortages, particularly in challenging years like 2223. This extended the period during which the landscape could sustain the duck population, highlighting the importance of managing goose competition to improve habitat sufficiency.

Diet Composition

Figure 14 displays the proportion of diet made up of moist soil seeds, rice, and invertebrates for each goose treatment across all scenarios. Increased goose competition limited the availability of rice for ducks, particularly in challenging years.

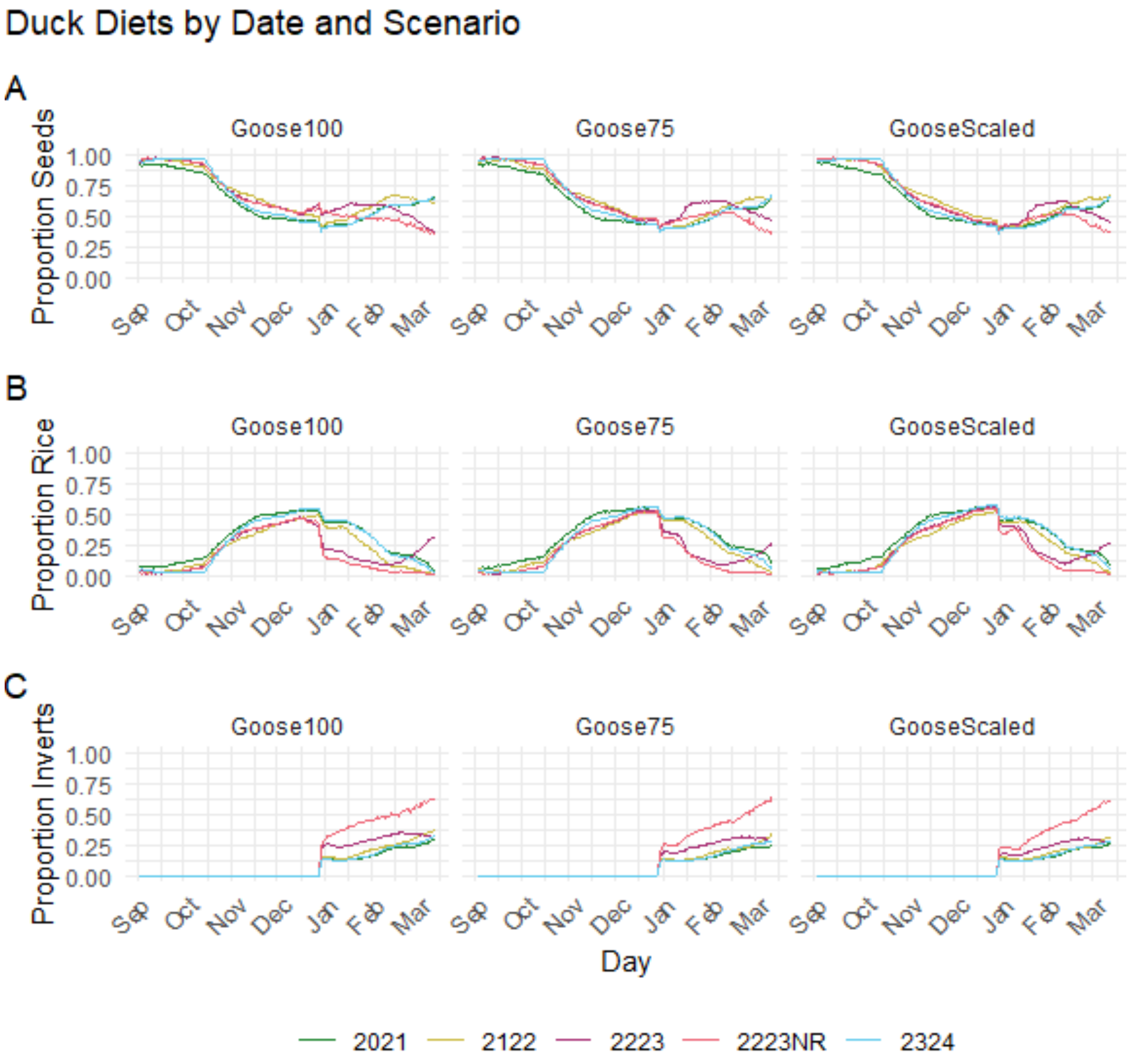


Figure 14. Duck Diet by Date for Five Habitat Scenarios.

In scenarios with high goose competition (Goose100), ducks were forced to rely more on less-preferred food sources like invertebrates, especially in years with limited rice availability (e.g., 2223). Goose75 and GooseScaled treatments allowed ducks to maintain a higher proportion of rice in their diet, which is more energetically favorable.

Foraging Flight Distances

Figure 15 shows average foraging flight distances by day for each scenario, paneled by goose treatment. The figure demonstrates increased flight distances as resources become scarce and competition intensifies.

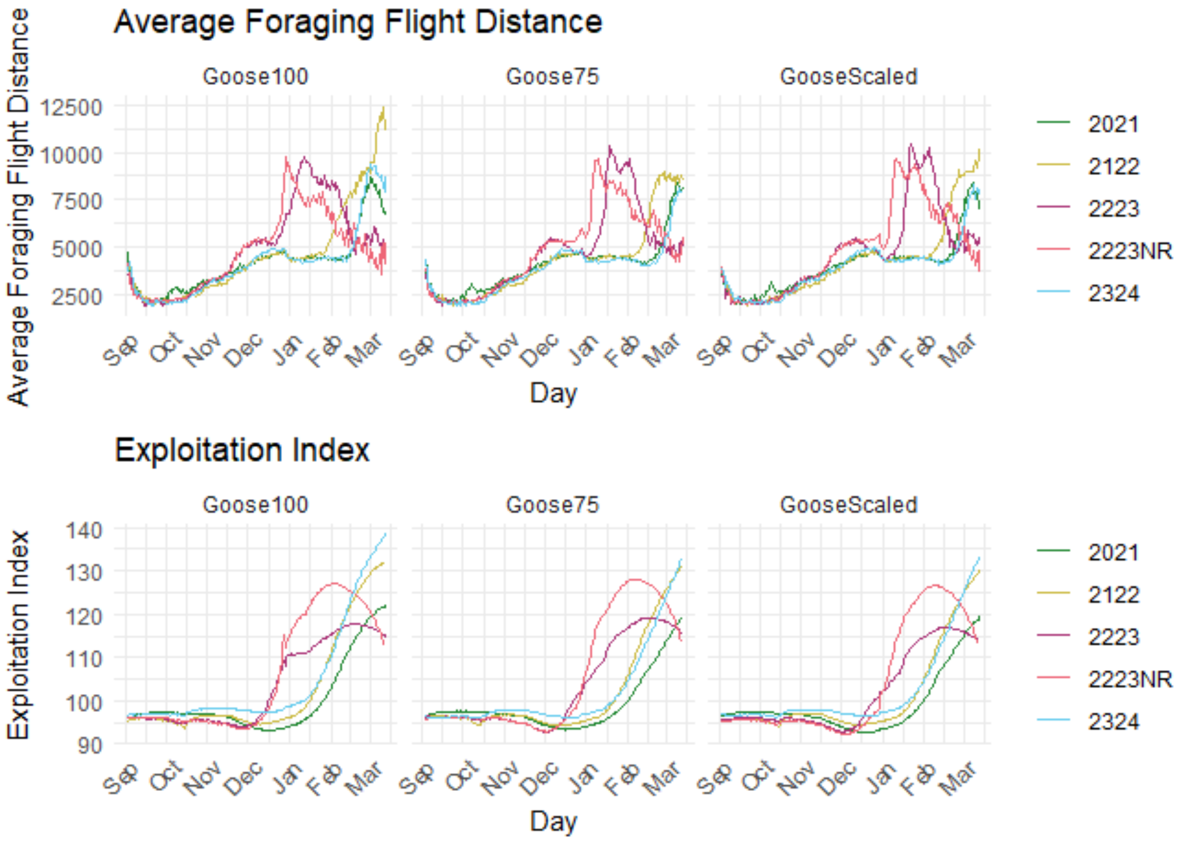


Figure 15. Foraging Flight Distance and Exploitation Index for Five Habitat Scenarios.

As food resources became limited, ducks in challenging scenarios (e.g., 2223) had to travel longer distances to find sufficient forage, particularly under the Goose100 treatment. Goose75 and GooseScaled treatments reduced the need for extended foraging flights, helping to conserve energy and maintain body condition.

Exploitation Index

Figure 15 shows the exploitation index by day for each scenario, indicating the degree of resource depletion near roost sites.

The exploitation index increased earlier in Goose100 treatments, indicating faster resource depletion near roosts. Goose75 and GooseScaled treatments reduced the rate of depletion, allowing ducks to maintain more stable foraging conditions throughout the season.

3.2.5 Summary and Management Implications

***Key Takeaways**:* Goose100 places the most stress on duck populations, leading to earlier population declines, increased foraging distances, and lower lipid reserves. Goose75 and GooseScaled provide a buffer that extends population viability and resource availability, particularly in challenging years like 2223 and 2122. The 2122 year is on the borderline of being able to sustain the SVExtended chronology, which is the most challenging, particularly if the Goose scenario is relieved slightly (as in GooseScaled) suggesting that the ~412,000 acres of rice available in this scenario (228,000 winter flooded) is right around the minimum necessary to sustain the population.

Table 11: Summary Metrics for GooseScaled/SVExtended Scenario

Scenario	Pop150	DUD%	50% Day	Migrant Lipids	EDDR Min	DTD
2021	94.1 %	97.1 %	Last day: 61.6 %	1760	Day 194 - Min: 26.8	Day 167
2122	92.8 %	95.7 %	Day 195	1524	Day 177 - Min: 28.4	Day 152
2223	51 %	82.1 %	Day 151	794	Day 142 - Min: 20.9	Day 122
2223NR	24.2 %	74.7 %	Day 138	555	Day 129 - Min: 10.6	Day 117
2324	93.2 %	97 %	Last day: 74.5 %	1819	Day 189 - Min: 34.5	Day 166

Management Recommendations: To mitigate the impacts of interspecies competition, it is crucial to ensure sufficient wetland and rice acreage, especially during challenging years. While the 2122 year appears to be on the edge of being able to support the target population, this is because it provides enough food for the ducks AFTER the geese have taken their share. If the goose pressure increases, or if they receive 100% of their energy requirements from rice and corn, then more wetland or rice habitat will be necessary. Habitat management strategies should focus on optimizing the spatial and temporal distribution of both duck and goose populations to sustain both populations.

3.3 Experiment 2. Population Chronologies

In Experiment 2, we examined how different population chronologies affect habitat sufficiency for wintering duck populations in the Central Valley. The goal was to evaluate the impact of the timing and abundance of duck arrivals on resource availability and population health throughout the winter season. For this experiment, we used the median habitat scenario (2122) with the highest level of goose competition (Goose100) to explore the influence of four population chronologies: SV, SVDelayed, SVExtended, and JVTarget.

3.3.1 Duck Populations under Different Chronologies

Figure 16: This figure shows the trajectories of duck populations under each of the four chronologies. The SV chronology, which represents typical arrival and departure patterns, maintains the highest population level throughout the winter, while SVExtended, which has higher population pressure early in the season, shows the earliest and steepest decline.

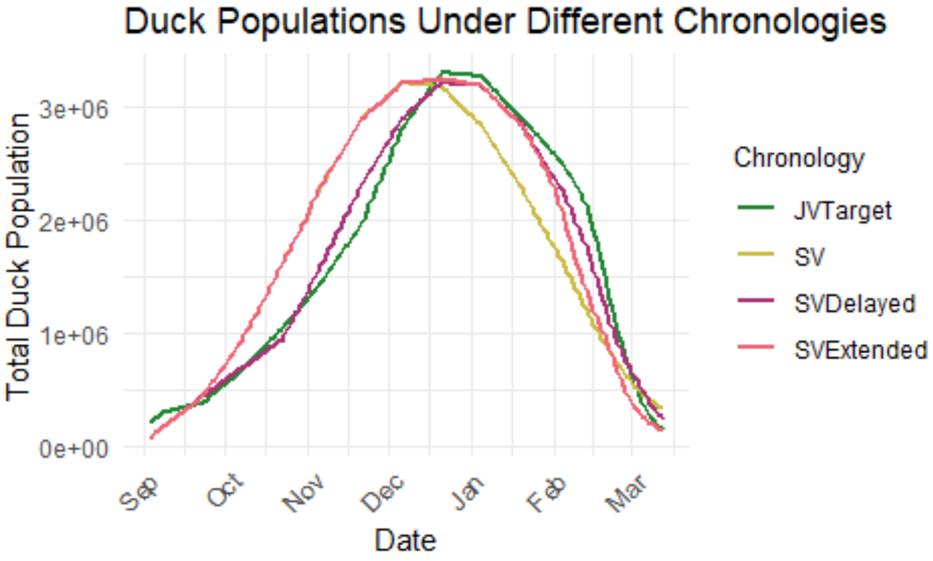


Figure 16. Duck Populations Under Different Chronologies.

Table 12. Percent of target population on day 150 (Feb. 1). We consider a population >90% of target on this day to be meeting expectations.

Table 12: Percent of Target Population on Day 150

Scenario	JVTarget	SV	SVDelayed	SVExtended
2122	96.1 %	92.9 %	94.8 %	93.4 %

Table 13. Total duck use days over the season for each scenario, and the percentage of the target duck use days attained based on the SVExtended Chronology.

Table 13: Total Duck Use Days Compared to JVTarget

Scenario	JVTarget	SV	SVDelayed	SVExtended
2122	93 %	94.2 %	92 %	99.3 %

The results highlight the significant influence of population arrival timing on habitat sufficiency. SV, with an early peak and gradual decline, was better able to maintain a healthy population throughout the winter. In contrast, SVExtended placed greater pressure on the landscape early on, leading to rapid declines in population by late January.

Table 14: Aggregate Metrics of Emigrant Timing and Lipid Levels by Scenario

Scenario Type	Total Emigrants	Weighted Avg Emigration Day	Weighted Mean Emigrant Lipids	Total Lipid Energy (Emigrants + Residents)
JVTarget	3,128,000	166	964	3,121,781,407
SV	3,113,700	150	1,466	4,868,764,384
SVDelayed	3,177,000	161	1,173	3,901,423,164
SVExtended	3,256,700	158	1,005	3,368,242,099

Percent of Target Population

Figure 17: This figure illustrates the percentage of the target population maintained under each chronology. SVExtended begins to fall first, around the beginning of February, and falls furthest, reaching only about 30% of the target by the end of the season. SVDelayed and JVTarget follow similar patterns, both crossing below 50% by mid-March. The SV chronology is the only one that maintains over 50% of the population until the end of the simulation.

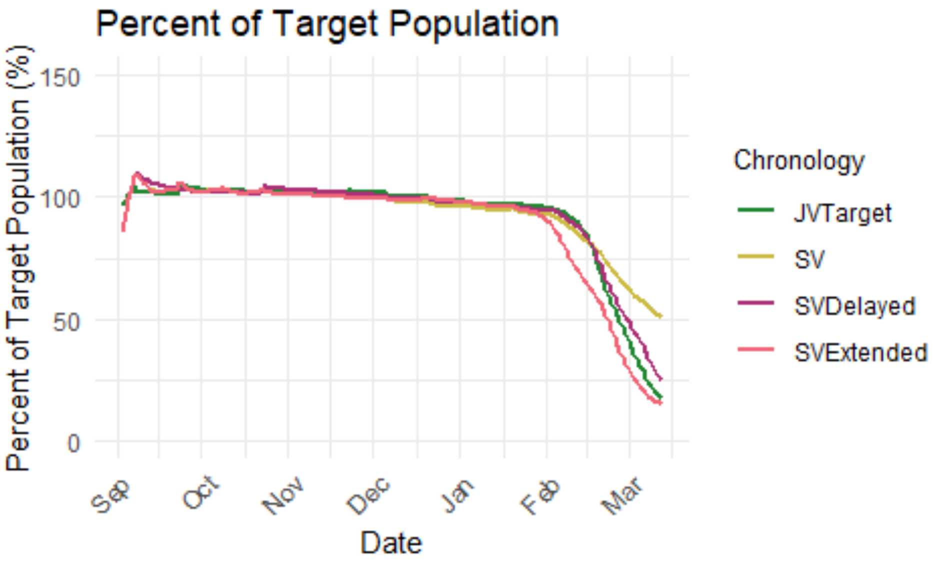


Figure 17. Percent of Chronology Target Population.

Table 15: A table summarizing the day on which each population fell below 50% of the target, or the percentage of the target population on the last day if it remained above 50%.

Table 15: Day on Which Population Falls Below 50 Percent of Target, OR Percent of Target on Day 195

Scenario	JVTarget	SV	SVDelayed	SVExtended
2122	Day 180	Last day: 50.1 %	Day 183	Day 176

The results indicate that the landscape can more effectively support early population pressure, as evidenced by the SV chronology maintaining higher population levels compared to those with increased late-season pressures (SVDelayed, JVTarget, and SVExtended). This suggests that the timing of habitat use is crucial for sustaining populations, particularly in challenging years.

3.3.2 Energy Demand Days Remaining (EDDR)

Figure 18: The EDDR figure compares the energy available relative to daily demand under each chronology. SV starts with a lower EDDR than JVTarget or SVDelayed but diverges from SVExtended in late January, ending with the highest EDDR through February and March. SVExtended hits a minimum in late January, while JVTarget and SVDelayed experience very low minima in mid to late March. SV, however, hits a minimum in early March, but the level is much higher than other treatments due to the reduced population pressure aligning with decreasing food availability.

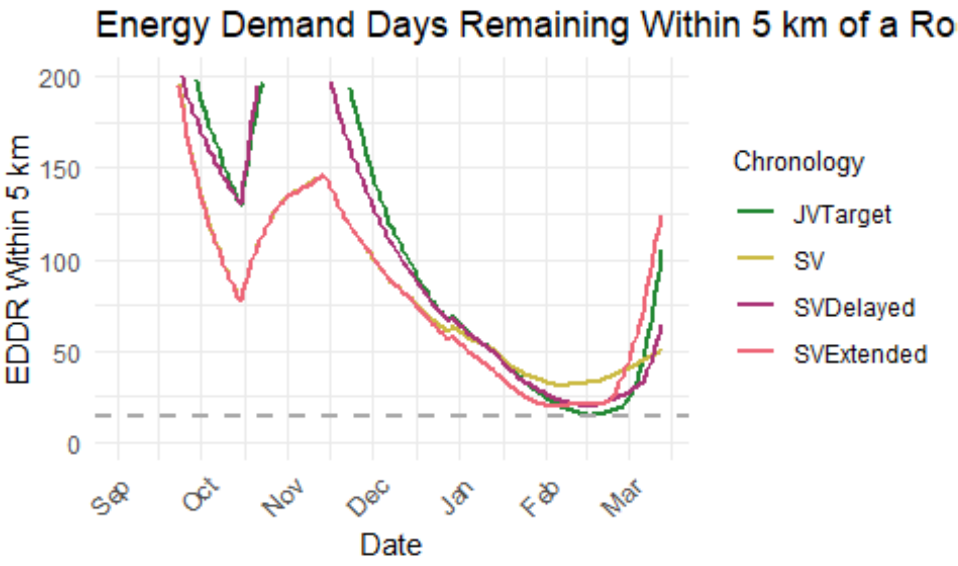


Figure 18. Energy Demand Days Remaining Within 5km of a Roost by Chronology.

Table 16: Minimum Energy Demand Days Remaining Day and Level

Scenario	JVTarget	SV	SVDelayed	SVExtended
2122	Day 169 - Min: 14.8	Day 161 - Min: 31.3	Day 170 - Min: 19.6	Day 157 - Min: 19.5

The analysis reveals that SVExtended was the most stressful chronology for ducks, as evidenced by the early EDDR minimum in late January. In contrast, SV maintained a higher EDDR through March, indicating that population pressure reduced along with food availability, which allowed the remaining individuals to better sustain themselves. This underscores the importance of matching population arrival and departure patterns to resource availability.

3.3.3 Daily Net Energy Balance and Days to Deficit (DTD)

Figure 19: The daily net energy balance plot shows the divergence of chronologies from late January onwards. SV maintains a higher energy balance in February and March, while the other chronologies experience negative energy balances.

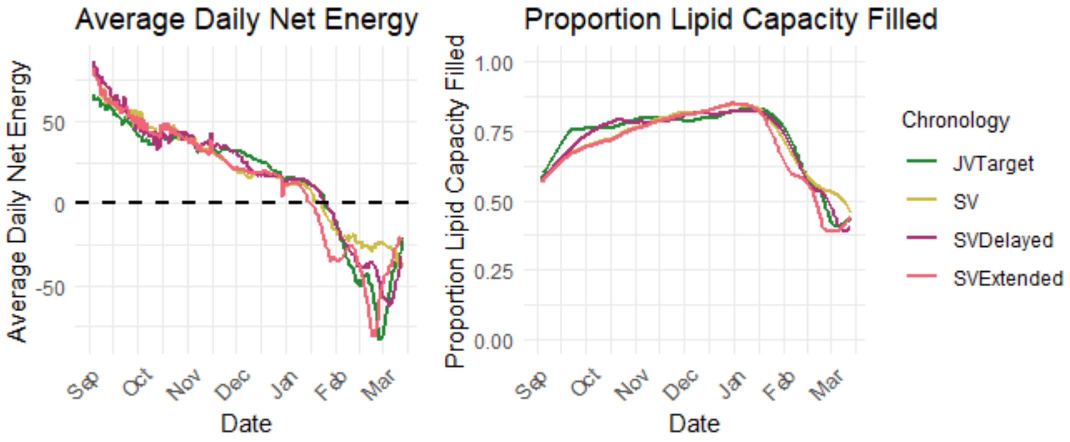


Figure 19. Energetics by Chronology.

Table 17: A table summarizing Days to Deficit (DTD) for each chronology, indicating when ducks begin to experience a negative energy balance.

Table 17: Days to Deficit (DTD) by Scenario

Scenario	JVTarget	SV	SVDelayed	SVExtended
2122	Day 148	Day 145	Day 149	Day 138

The SV chronology had the second earliest DTD, occurring in late January. However, unlike the other chronologies, the energy balance under SV never fell far into the negative, and by March, it was the only treatment where ducks maintained more than 50% of their lipid capacity. This demonstrates that while the SV chronology may experience early stress, it results in a more sustainable outcome for the population in the later months.

3.3.4 Summary and Management Implications

Key Takeaways*:* The SVExtended chronology places the greatest stress on the duck population, leading to early declines in population size, energy balance, and lipid reserves. The SV chronology, on the other hand, maintains the population and lipid reserves more effectively through the end of the winter season.

Table 18: Summary Metrics for Goose100/2122 Scenario

Scenario	Pop150	DUD%	50% Day	Migrant Lipids	EDDR Min	DTD
JVTarget	96.1 %	93 %	Day 180	964	Day 169 - Min: 14.8	Day 148
SV	92.9 %	94.2 %	Last day: 50.1 %	1466	Day 161 - Min: 31.3	Day 145
SVDelayed	94.8 %	92 %	Day 183	1173	Day 170 - Min: 19.6	Day 149
SVExtended	93.4 %	99.3 %	Day 176	1005	Day 157 - Min: 19.5	Day 138

Management Recommendations: To support wintering duck populations effectively, it is crucial to align habitat availability with population arrival and departure patterns. Management actions should aim to optimize resource availability during peak population periods, particularly in late winter when food resources become limiting. Ensuring that habitat conditions are suitable for sustaining populations early in the season can alleviate pressure during the critical late-winter period, enhancing overall population resilience.

3.4 Experiment 3: Determining the Rice Acreage Threshold for Sustainable Duck Populations

3.4.1 Overview and Motivation

- **Objective**: The primary goal of this experiment was to determine the minimum flooded rice acreage required to sustainably support wintering duck populations in California's Central Valley under both demanding and less-demanding conditions. We used 14 different acreage scenarios, ranging from 254,000 to 526,000 acres, to explore acreage thresholds for maintaining population health across varying levels of competition and environmental stress.
- **Experimental Design**: Two sets of simulations were conducted:
  - **Demanding Conditions**: Goose100 and SVDelayed treatments were applied to simulate challenging conditions for the ducks.
  - **Less-Demanding Conditions**: GooseScaled and SV treatments were used to simulate more favorable conditions, allowing us to examine whether the acreage thresholds would be lower in less competitive scenarios.
- **Key Metrics**: The following metrics were employed to evaluate habitat sufficiency across the different rice acreage scenarios:
  - **Days to Deficit (DTD)**: The number of days before ducks begin to experience negative net energy balance.
  - **Population on February 1 (% of target)**: The percentage of the target population present at the midpoint of winter (Day 150).
  - **Day Population Falls Below 50% of Target**: The day when the population drops below half of the target size.
  - **Population on March 15 (% of target)**: The percentage of the target population on the last day of simulation (Day 195).
  - **Earliest Expected Energy Depletion Day (EEDDR)**: The day at which energy resources are projected to fall below sustainable levels.
  - **Total Duck Use Days**: Cumulative number of duck use days, representing habitat use.
  - **Weighted Emigrant Energy**: The average energy reserves of emigrating ducks, providing an indication of emigration health.
  - **Total Duck Energy**: Combined energy of emigrants and residents, assessing total population energy retention.

- **Assessing Habitat Sufficiency**: We used these metrics to assess the rice acreage required to sustain the target duck population at optimal levels. Each acreage scenario was categorized based on its ability to meet sufficiency thresholds under both demanding and less-demanding conditions:
  - **GREEN**: Metrics above sufficiency thresholds for both demanding and less-demanding conditions.
  - **YELLOW**: Metrics above sufficiency thresholds only for less-demanding conditions.
  - **RED**: Metrics below sufficiency thresholds for both conditions.
- **Setting Sufficiency Thresholds**: The sufficiency threshold for each metric was determined based on the acreage value at which that metric approached an asymptote under demanding conditions. This approach was chosen to identify the point at which increasing rice acreage no longer produced substantial gains in duck population health or habitat sufficiency, effectively providing a conservative estimate of what is required to meet the needs of the population under the most challenging conditions modeled. The asymptote indicates the point of diminishing returns—where additional rice acreage has minimal added benefit. This conservative threshold ensures that the habitat can sustain duck populations at or near target levels, even during years with higher competition or lower resource availability. It is important to note, however, that these thresholds do not necessarily define the minimum amount of habitat that could be acceptable; rather, they identify the level of habitat that fully supports population needs without significant further benefit from additional acreage. The decision on what constitutes an "acceptable" level of habitat support is ultimately a policy question, and stakeholders must weigh costs, benefits, and trade-offs based on these thresholds and their associated implications.

3.4.2 Figures and Results

Key Metrics vs. Rice Acreage

Days to Deficit (DTD):

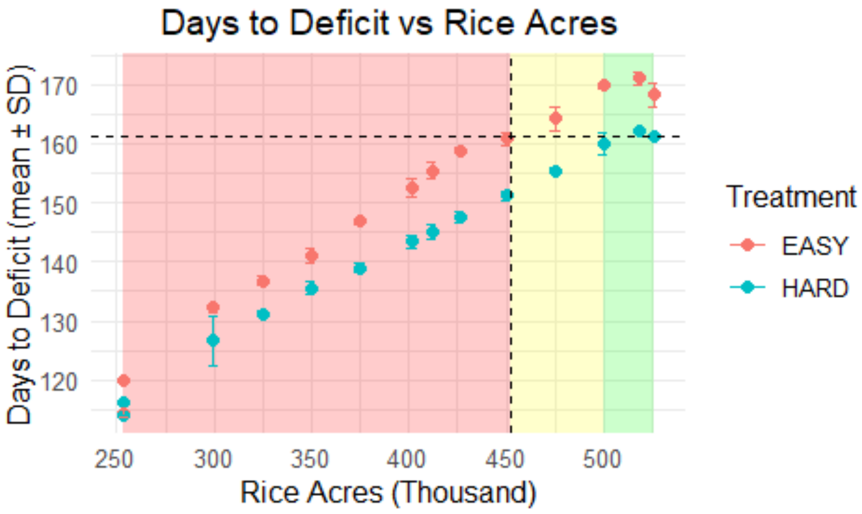


Figure 20. Days to Deficit versus Rice Acreage for Demanding and Less-Demanding Treatments

Narrative: Days to Deficit asymptotes above 500,000 acres at around 160-162 days for demanding conditions, while less-demanding conditions reach an asymptote between 450,000-475,000 acres at around 170 days. This suggests that 500,000 acres is sufficient for both conditions, while 450,000-475,000 acres may be marginal (YELLOW) under less-demanding conditions.

- ***Population on February 1 (% of target)***:

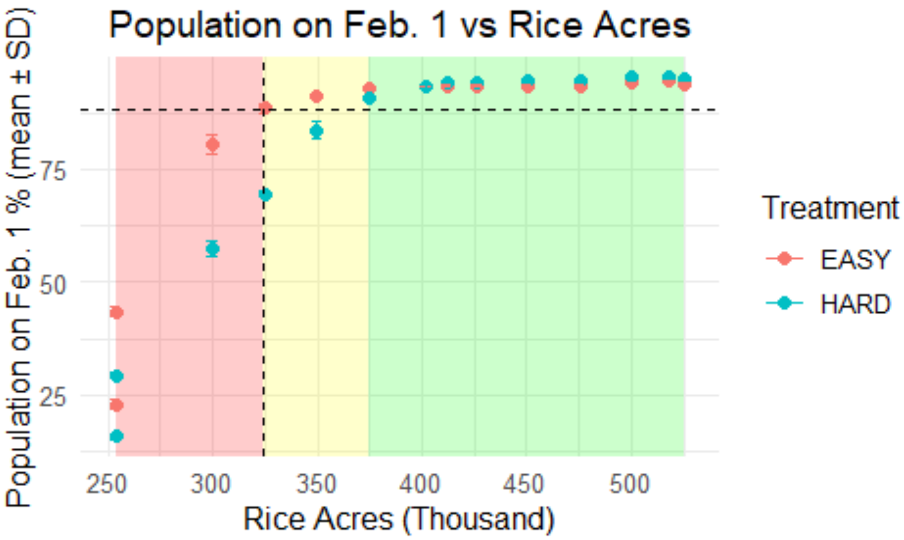


Figure 21. Population Percentage on February 1 versus Rice Acreage for Demanding and Less-Demanding Treatments.

Narrative: Population levels on February 1 reach 88% for both demanding and less-demanding conditions at 375,000 rice acres. In demanding conditions, the population achieves 90-93% of the target above 400,000 acres. Under less-demanding conditions, the population asymptotes close to the same level (88-90%) at 375,000-400,000 acres. This indicates that 400,000 acres may suffice in favorable scenarios, but under demanding conditions, anything below 400,000 acres is marginal.

- ***Day Population Falls Below 50% of Target:***

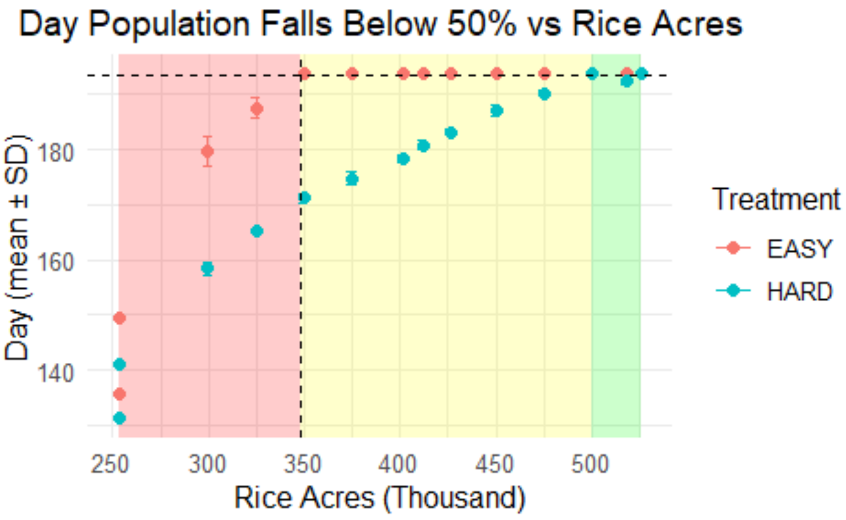


Figure 22. Days Population Falls Below 50% of Target versus Rice Acreage for Demanding and Less-Demanding Treatments.

Narrative: Under demanding conditions, the population falls below 50% at day 193 for acreages above 500,000. In less-demanding conditions, this occurs around 350,000. This suggests that a range of 350,000-500,000 acres could support the population, but a safer threshold is 500,000 acres to ensure resilience.

- ***Population on March 15 (% of target):***

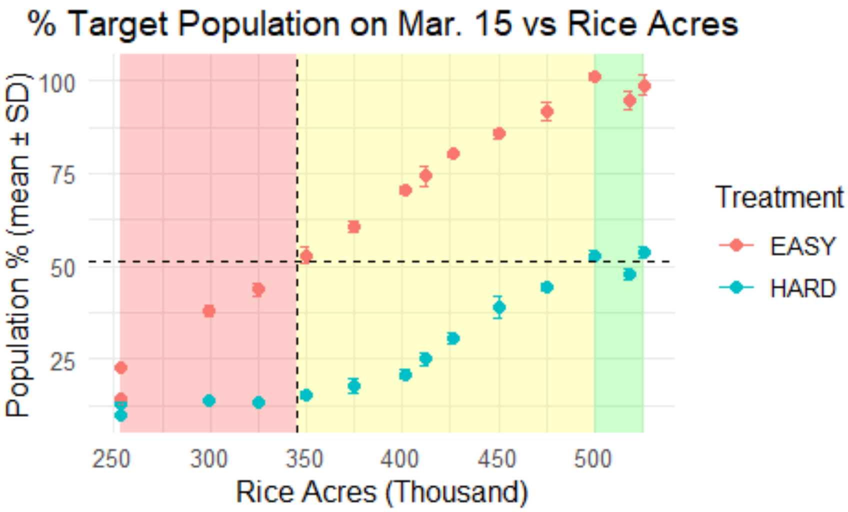


Figure 23. Percent of Target Population on March 15 versus Rice Acreage for Demanding and Less-Demanding Treatments.

Narrative: For demanding conditions, the population on the final day of the simulation asymptotes at 45-50% above 500,000 acres. Under less-demanding conditions, 350,000 acres is sufficient to achieve this level, and acreages above 500,000 acres maintain 91-95%. The result suggests that maintaining over 500,000 acres is optimal, while 350,000-500,000 acres can be considered marginal.

- ***Earliest Expected Energy Depletion Day:***

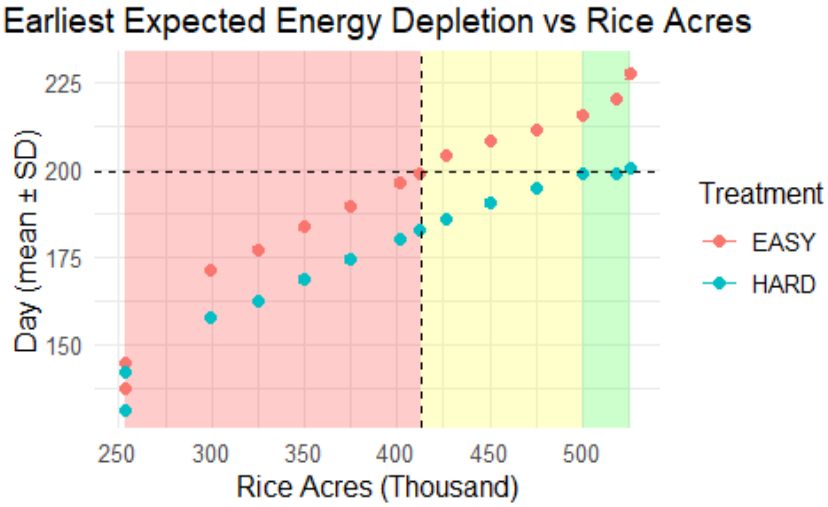


Figure 24. Earliest Expected Energy Depletion Date versus Rice Acreage for Demanding and Less-Demanding Treatments.

Narrative: Under demanding conditions, the population's earliest expected energy depletion day asymptotes at around day 200 above 500,000 rice acres. In less-demanding conditions, this level is reached between 412,000-425,000 acres. This suggests that a range of 412,000-500,000 acres is in our marginal YELLOW range, but the safer GREEN threshold of 500,000 acres ensures population survival.

- ***Total Duck Use Days***:

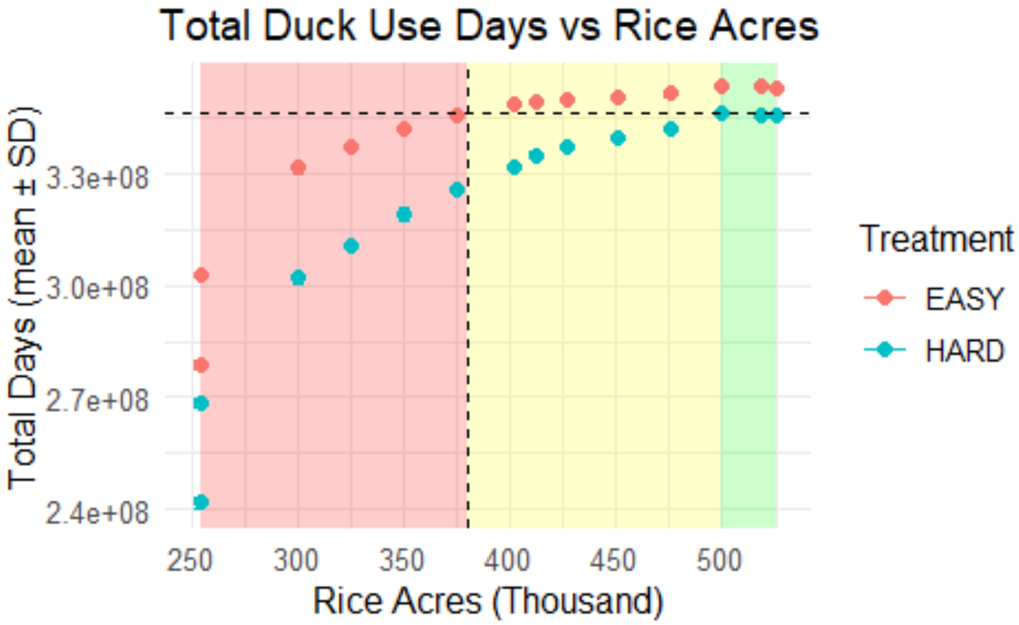


Figure 25. Total Duck Use Days versus Rice Acreage for Demanding and Less-Demanding Treatments.

Narrative: Total Duck Use Days reach ~346 million for demanding conditions above 500,000 acres, whereas less-demanding conditions achieve this level around 375,000 acres. This highlights that less acreage is required to meet usage goals when competition is managed, though 500,000 acres remains a robust target

- ***Weighted Emigrant Energy & Total Duck Energy:***

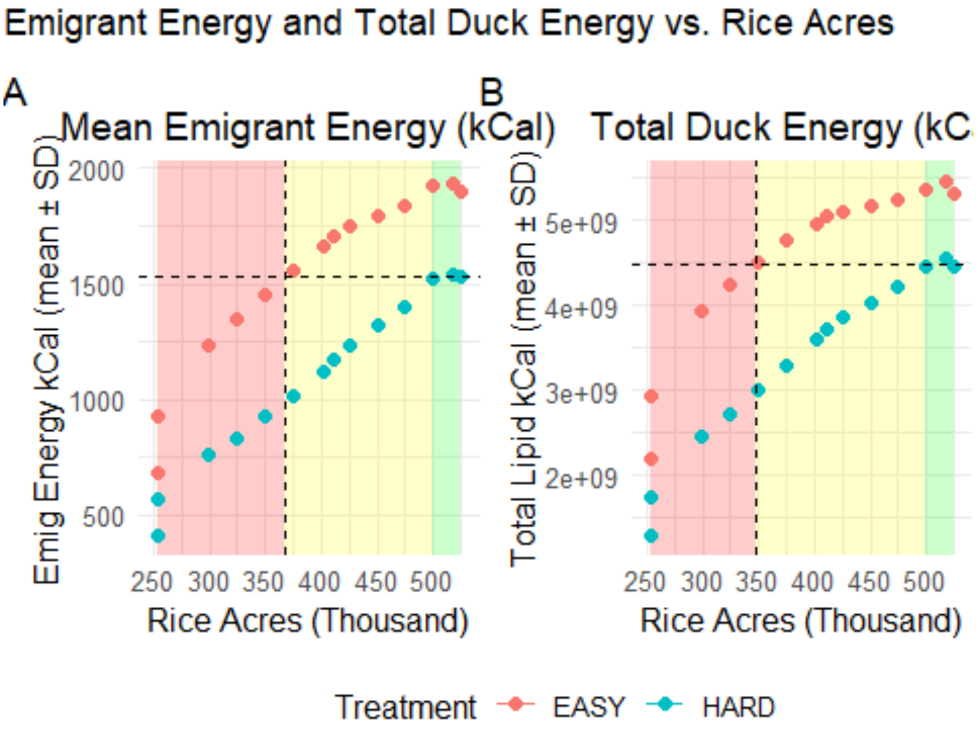


Figure 26. Mean emigrant energy and total duck energy versus rice acreage for Demanding and Less-Demanding treatments.

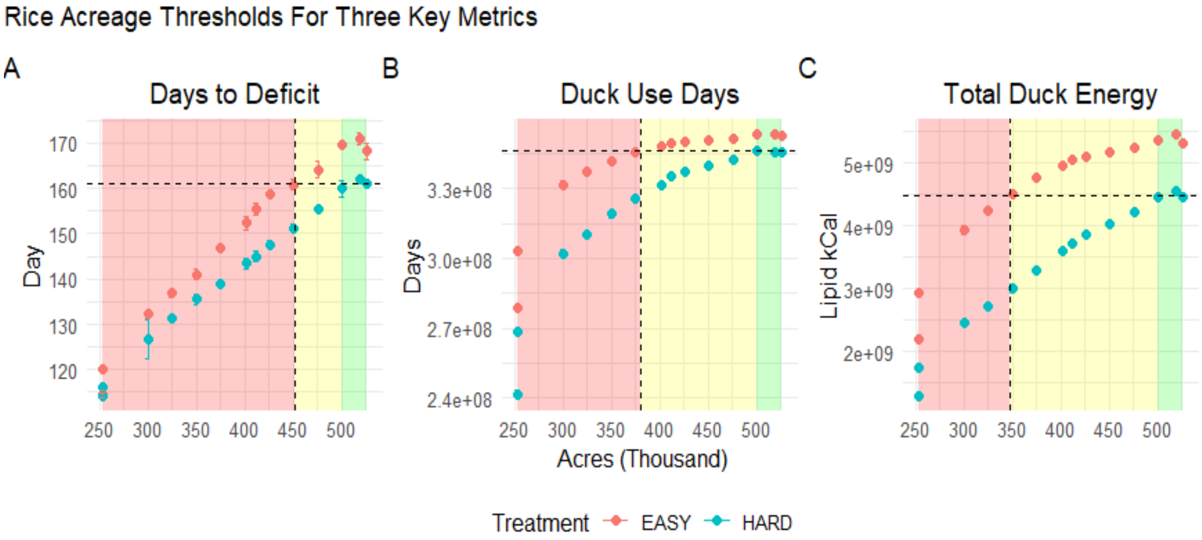


Figure 27. Rice Acreage Thresholds for Three Key Metrics. A) Days to Deficit, B) Duck Use Days, C) Total Duck Energy

Narrative: Weighted Emigrant Energy asymptotes at 1526-1537 kcal above 500,000 acres for demanding conditions, whereas less-demanding conditions reach this around 370,000 acres. Total

Duck Energy shows a similar trend, indicating the ability of ducks to maintain energy reserves is enhanced at higher acreages, but with less competition, even 350,000-375,000 acres may be sufficient.

Summary of Results and Implications:

- **Optimal Acreage Threshold**:
  - Based on demanding condition simulations, the key metrics consistently suggest an **asymptote above 500,000 acres**. This indicates that for ensuring a stable and resilient duck population during challenging conditions, maintaining at least **500,000 acres** of flooded rice is essential.
  - Under less-demanding conditions, many metrics reach sufficiency thresholds at **350,000-375,000 acres**. This implies that **375,000 acres** could suffice in more favorable scenarios where competition and environmental stress are reduced, providing a cost-effective habitat management target.
- **Figures to Highlight**:
  - **Time Series Plots**: Including time series plots is not strictly necessary for all metrics but could be helpful for **Population Dynamics** and **Available Energy** over time to illustrate differences between acreage scenarios. This would provide additional context to the summary plots for visualizing temporal shifts.

3.4.3 Time Series Analysis of Red/Yellow/Green Scenarios

The time series figures presented below provide a detailed comparison of key metrics for a **GREEN** scenario (500,000 rice acres), a **YELLOW** scenario (400,000 rice acres), and a **RED** scenario (300,000 rice acres), under both the **EASY** (dashed lines) and **HARD** (solid lines) conditions.

Population Dynamics Over Time

Figure 28 illustrates changes in the population and percent of target population over the course of the winter season. As expected, higher rice acreage results in greater population stability, particularly later in the season. The **GREEN** scenario shows the highest population persistence, with little decline until late in the season, while the **RED** scenario experiences earlier and steeper population declines. The effects of rice acreage are especially pronounced under the **HARD** treatment, where increased competition for resources drives rapid population reductions as food becomes scarcer. This divergence in population trajectories between **EASY** and **HARD** scenarios underscores the critical role that interspecific competition and acreage availability play in determining duck population viability.

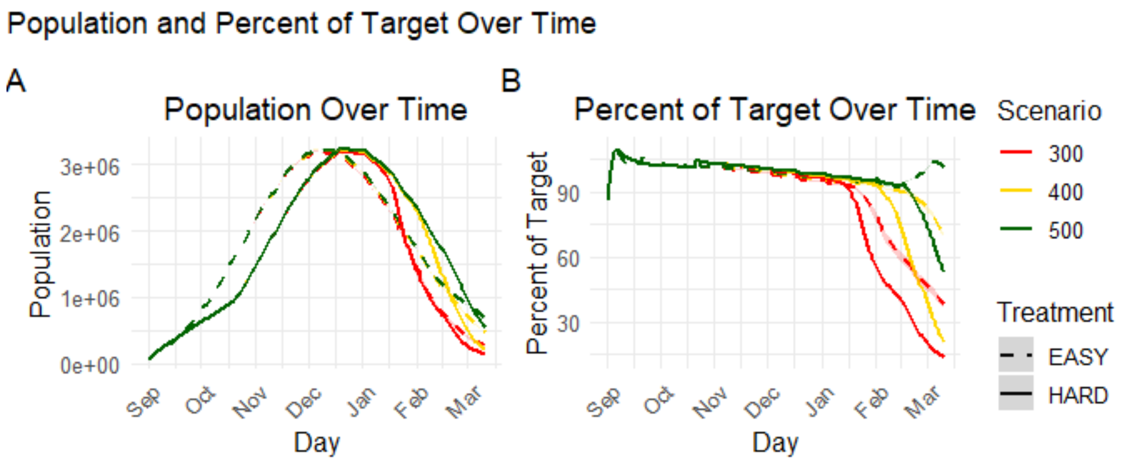


Figure 28. Duck Population and Percent of Target by Date Red/Yellow/Green Scenarios and Easy/Hard Treatments.

Landscape Energy Availability

As expected, the amount of available landscape energy reaches higher levels in higher rice acreage scenarios. For each of the rice acreage scenarios, the available landscape energy is initially lower in the EASY treatment (Figure X), as duck foraging is initially higher due to increased early population pressure. However, as we get into January, there is then more energy available on the landscape in the EASY treatment as goose and duck foraging is more intense in the HARD treatments later in the season.

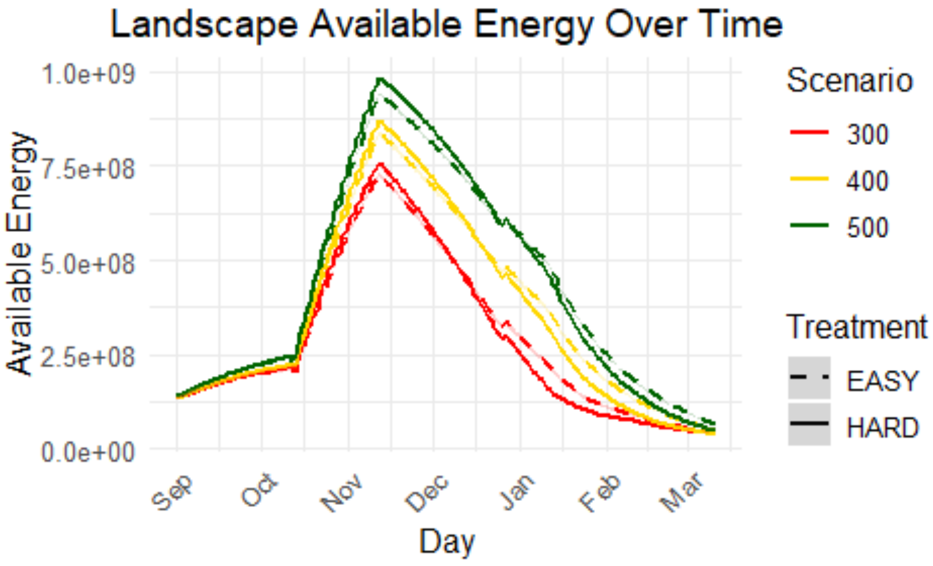


Figure 29. Landscape Available Energy by Date Red/Yellow/Green Scenarios and Easy/Hard Treatments.

Energetics and Lipid Reserves

The impact of rice acreage and interspecies competition on duck energetics is shown in **Figure 30**, focusing on lipid reserves and daily net energy. In the **HARD** treatment, lipid accumulation initially progresses well during the early season but falls off as resource competition intensifies. In contrast, the **EASY** treatment allows for more gradual lipid accumulation through September and October, ultimately reaching higher peaks by mid-November. Increased rice acreage leads to delayed declines in daily net energy and higher overall lipid peaks, suggesting that a greater habitat buffer is critical for sustaining duck body condition into late winter.

The **YELLOW** and **RED** scenarios demonstrate markedly different outcomes for lipid reserves, with **RED** scenarios showing more rapid drops during critical late-winter months. In all scenarios, the **EASY** treatment mitigates energy loss, reinforcing the importance of reduced competition.

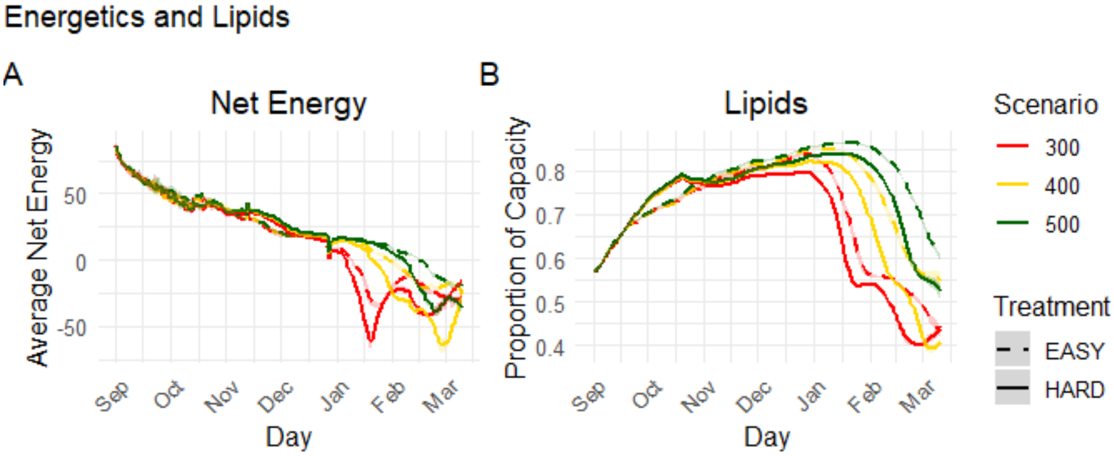


Figure 30. Duck Energetics by Date Red/Yellow/Green Scenarios and Easy/Hard Treatments.

Energy Demand and Depletion

The **Energy Demand Days Remaining (EDDR)** and **Earliest Expected Energy Depletion Day (EEDDR)** are presented in **Figure 31**. These metrics help indicate when critical energy shortages are likely to occur. In **RED** scenarios, the EEDDR is reached by mid-January, while **YELLOW** and **GREEN** scenarios reach this critical point much later, with the **GREEN** scenario reaching it as late as March under the **EASY** treatment. The **HARD** treatment highlights more severe challenges—especially in **RED** scenarios—where EEDDR values indicate minimal available energy remaining relative to expected needs for the season. This trend emphasizes that mid-January is a critical period for managing habitat sufficiency, particularly when habitat conditions are challenging, and competition is high.

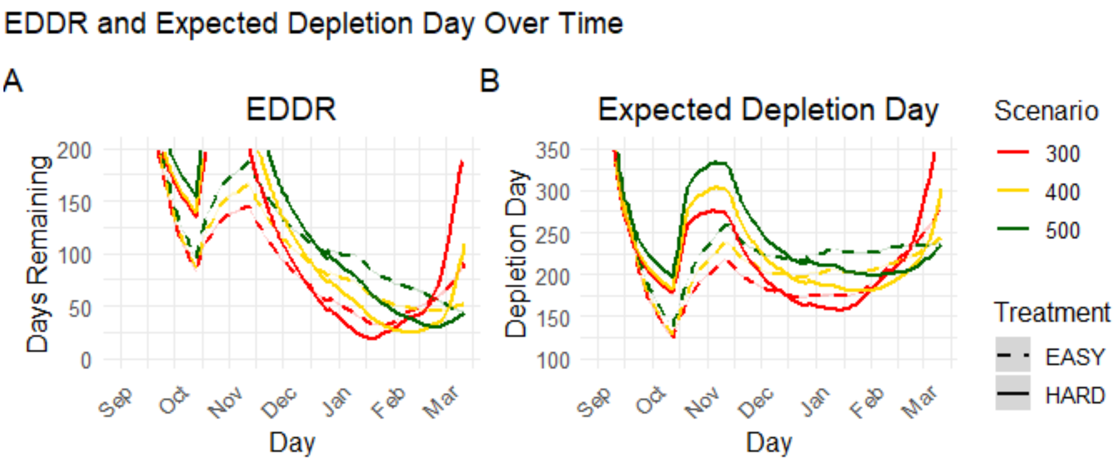


Figure 31. EDDR and Expected Depletion Day by Date Red/Yellow/Green Scenarios and Easy/Hard Treatments.

Foraging Flight Distances and Exploitation

Higher rice acreage also mitigates the need for extended foraging flights, as illustrated in **Figure 32**. In the **RED** scenario, average foraging flight distances increase from approximately 5 km to 8 km during mid to late January. By contrast, in the **GREEN** scenario, this increase is delayed until late February, and even into March under the **EASY** treatment. This delay in increased foraging distances corresponds to improved energy conditions and greater food availability closer to roosting sites. **Figure 32** also shows a similar pattern with the **Exploitation Index**, which spikes late in the season, indicating decreased availability of resources near roosts. In **RED** scenarios, this spike occurs in January, whereas in **GREEN** scenarios, the spike is delayed until February or later, further emphasizing the impact of habitat sufficiency on the availability of accessible resources.

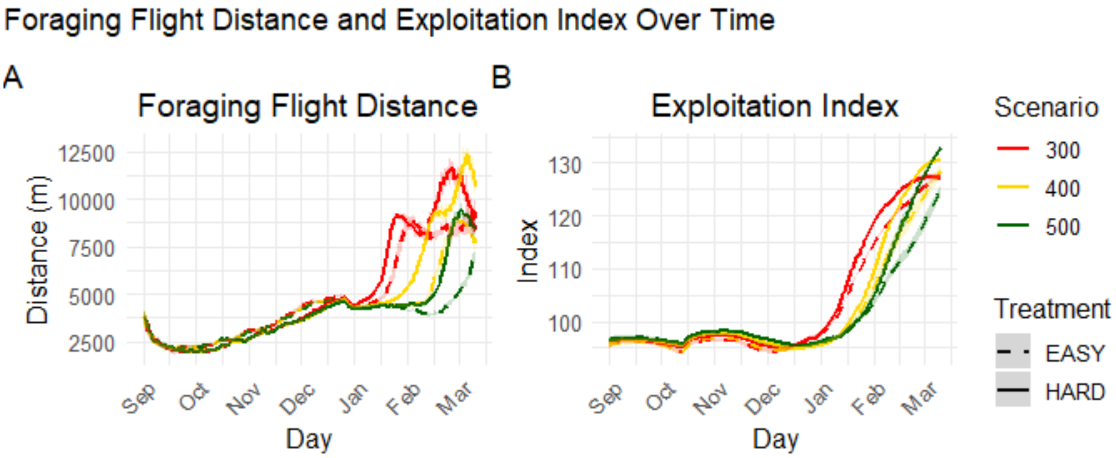


Figure 32. Flight Distance and Exploitation Index by Date Red/Yellow/Green Scenarios and Easy/Hard Treatments.

Finally, **Figure 33** illustrates how rice acreage and competition affect diet composition over the winter season. In lower acreage (**RED**) scenarios, ducks become increasingly reliant on moist soil seeds and invertebrates as rice availability declines. In the **EASY** treatments, ducks are able to maintain a higher proportion of rice in their diet, as reduced competition with geese makes more rice accessible. This change in diet composition is a reflection of the habitat conditions—greater rice acreage not only increases the availability of rice but also maintains a stable energy supply longer into the season.

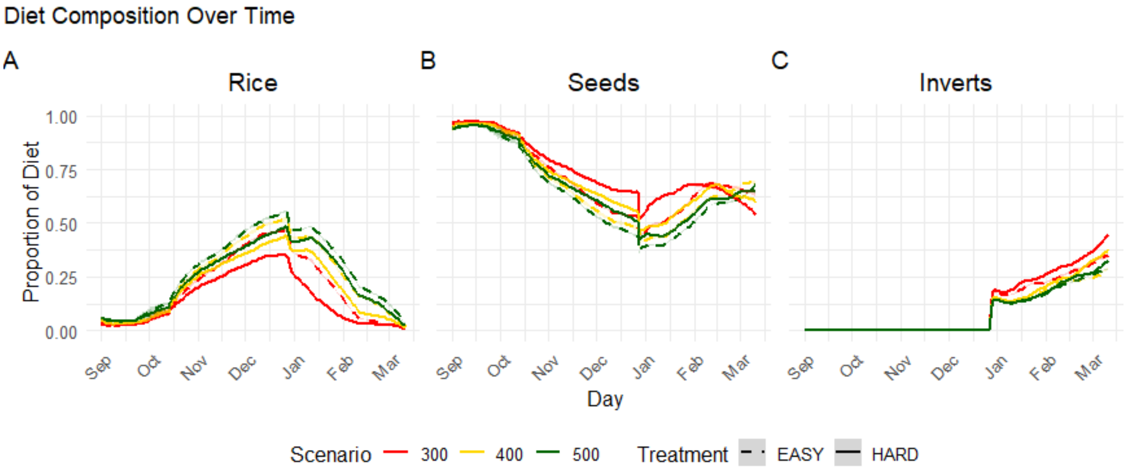


Figure 33. Duck Diet by Date Red/Yellow/Green Scenarios and Easy/Hard Treatments.

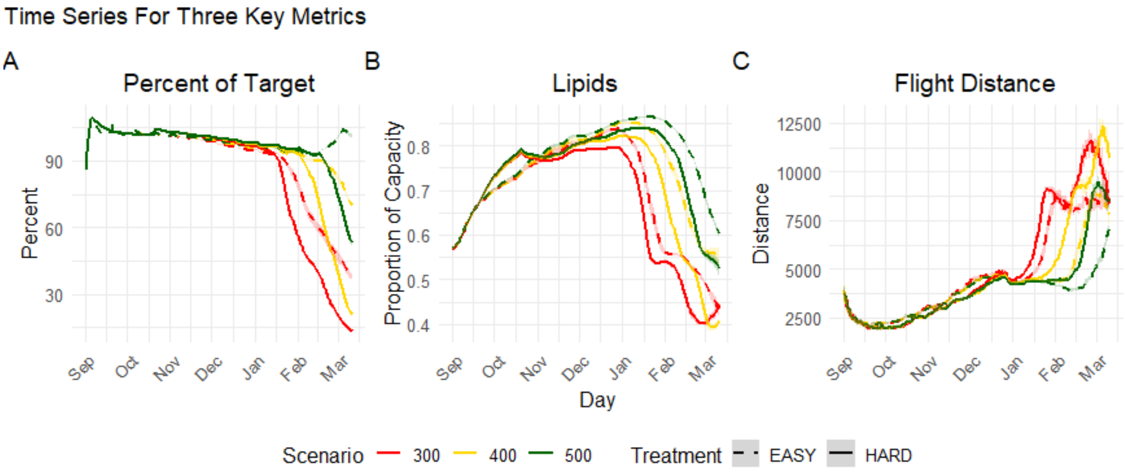


Figure 34. Rice Acreage Thresholds for Three Key Metrics. A) Days to Deficit, B) Duck Use Days, C) Total Duck Energy

3.4.4 Summary and Management Implications

- **Key Takeaways:**
    - Based on the demanding condition simulations, maintaining **500,000 acres** of flooded rice is the optimal threshold for supporting a stable and resilient duck population, especially during **challenging conditions** characterized by high competition (Goose100) and delayed migration (SVDelayed). This acreage level consistently resulted in **GREEN** outcomes across all key metrics, including high lipid reserves, delayed energy deficits, and extended population viability.

    - In more favorable conditions, such as reduced competition or alternative population chronologies (**EASY treatments**), **375,000 acres** may be sufficient to sustain duck populations without compromising key metrics like energy balance, lipid reserves, and population stability. Under these scenarios, key metrics remained within **YELLOW** thresholds, indicating a potential compromise that could still meet the ecological needs in less stressful years.
    - The asymptotic analysis of key metrics, such as Days to Deficit, Population on Day 150, and Day Population Falls Below 50%, suggests that maintaining flooded rice acreage at or above these thresholds ensures population health and resilience. However, the feasibility of maintaining 500,000 acres of flooded rice is a significant concern, particularly under drought conditions and associated water restrictions.
- **Challenges Related to Water Availability**:
    - **Water Scarcity and Variability**: The availability of water for flooding rice fields is highly variable, especially during drought years. Maintaining **500,000 acres** of flooded rice may not be feasible due to water availability constraints and high costs associated with water subsidies. Mid-January and February were highlighted as especially challenging periods under reduced acreage scenarios, with **RED** scenarios showing critical shortages during these months. This variability underscores the need for flexible water management that can respond to changing conditions while still supporting duck populations.
    - **Adaptive Thresholds for Drought Conditions**: Given that rice acreage tends to fluctuate based on water availability, aiming for 500,000 acres in drought years may be impractical or impossible without substantial water subsidies. In these situations, a more feasible target might be to focus on maximizing habitat efficiency through better water allocation strategies and targeting key areas that provide the most benefit to duck populations. Assessing the relative value of different locations is addressed in **Section 3.5**.
- **Management Recommendations**:
    - **Conservative Acreage Target**: In years with adequate water availability, efforts should focus on maintaining **at least 500,000 acres of rice**, including **approximately 260,000+ acres of winter-flooded rice**, to ensure optimal habitat for ducks, particularly under high competition or delayed migration conditions. This acreage provides resilience against fluctuations in population pressure and environmental stress.

    - **Adaptive Management During Drought**: During drought conditions, when 500,000 acres is unachievable, managers should adopt a **tiered approach**:

        - Aim for **375,000 acres as a minimum target**, recognizing that this may require additional support, such as enhancing managed wetland areas or prioritizing water-efficient regions.
        - **Strategic Habitat Concentration**: Focus on prioritizing specific basins or regions where waterfowl density is highest and where resource availability is likely to have the greatest impact. This targeted approach can help maximize the efficiency of limited water resources, particularly in **YELLOW** or **RED** scenarios, where habitat resources are more constrained. This targeted approach is based on implications from the broader literature but would require further validation specific to the Central Valley context.

        - **Maximizing Habitat Quality**: Consider management actions that enhance the quality of available flooded habitat, such as strategic flooding timing or managing competition more effectively. Although literature suggests these strategies could make a smaller acreage more effective, further research is needed to confirm their value specifically for the Central Valley environment.

    These recommendations are suggested based on insights from existing literature, but their efficacy for waterfowl in the Central valley would require additional focused research to validate and optimize.

- **Approach to Setting Sufficiency Thresholds**:
    - The sufficiency thresholds set in this analysis are **based on asymptotic behavior** observed in the simulations—specifically, the point at which increasing rice acreage provides **little additional benefit** to key population health metrics. This threshold represents the acreage needed to **support the target population at 100%**, with additional acres yielding minimal improvement.
    - **Policy Context**: It is essential to clarify that our approach is **not intended to define a definitive sufficiency threshold** for policy decisions. Instead, it serves as an **ecological benchmark** indicating the rice acreage required to fully support the target population under optimal conditions. The **degree to which a population can be sustained below this target**, while still deemed “sufficient,” is ultimately a **policy question**—one that involves broader societal, economic, and ecological considerations beyond the scope of this study.
    - **Implications for Decision-Makers**: The results presented here, including the graphs showing key metrics across varying rice acreages, provide **valuable insights** into what may be lost with each reduction in rice acreage. This information can help guide decision-makers in understanding the trade-offs involved and determining the **appropriate level of habitat support** that balances both ecological needs and resource constraints. Specifically, the impacts of falling below **375,000 acres** indicate a sharp decline in key metrics, transitioning from **YELLOW** to **RED** outcomes, suggesting the **375,000 acres** could serve as a critical lower limit in planning and resource allocation assuming no change in wetland habitat.

3.5 Spatial Prioritization of Rice

A critical aspect of managing rice acreage to sustain wintering duck populations in California’s Central Valley involves spatial prioritization—identifying which areas of rice should be prioritized to maximize ecological benefits, particularly in scenarios of limited water availability. In this section, we use multiple spatial analyses to classify the importance of different rice patches in the landscape based on their relative value for sustaining duck populations. Four main spatial analyses were conducted, with each rice patch categorized by distance to roost, duck usage, predicted use under different acreage scenarios, and a combined prioritization metric.

3.5.1 Distance to Roosting Sites

The distance between flooded rice fields and duck roosting locations is a critical factor influencing habitat quality and foraging efficiency. Figure 35 shows the classification terciles of rice areas by their proximity to roosting sites. The top tercile (based on total rice area) of areas within 1915 m of a roost are categorized as RED. Areas 1915-3750 m from a roost are in the middle tercile and are labeled in yellow, while the lowest tercile, those more than 3750 m away, are classified as GREEN.

We do not directly include distance to roost in our combined spatial prioritization, as it one of the key factors underlying usage (both in the real world and models), which we will focus on, and thus roost accessibility will be included implicitly in our prioritization. The results of this analysis highlight several key areas, however. Rice fields near roosts are predominantly found in the Colusa and Butte Basins, particularly those surrounding key refuge areas such as Sacramento, Delevan, and Colusa National Wildlife Refuges. Interestingly, despite a lack of total roost acreage, extensive portions of Sutter and the lower American Basin are still proximal to at least one roost site. Most of the rice acreage near the Yolo Bypass and parts of the Delta are also near roosts, while areas included the northern and western edges of Colusa, northeastern Sutter, and western Yolo have quite low roost access.

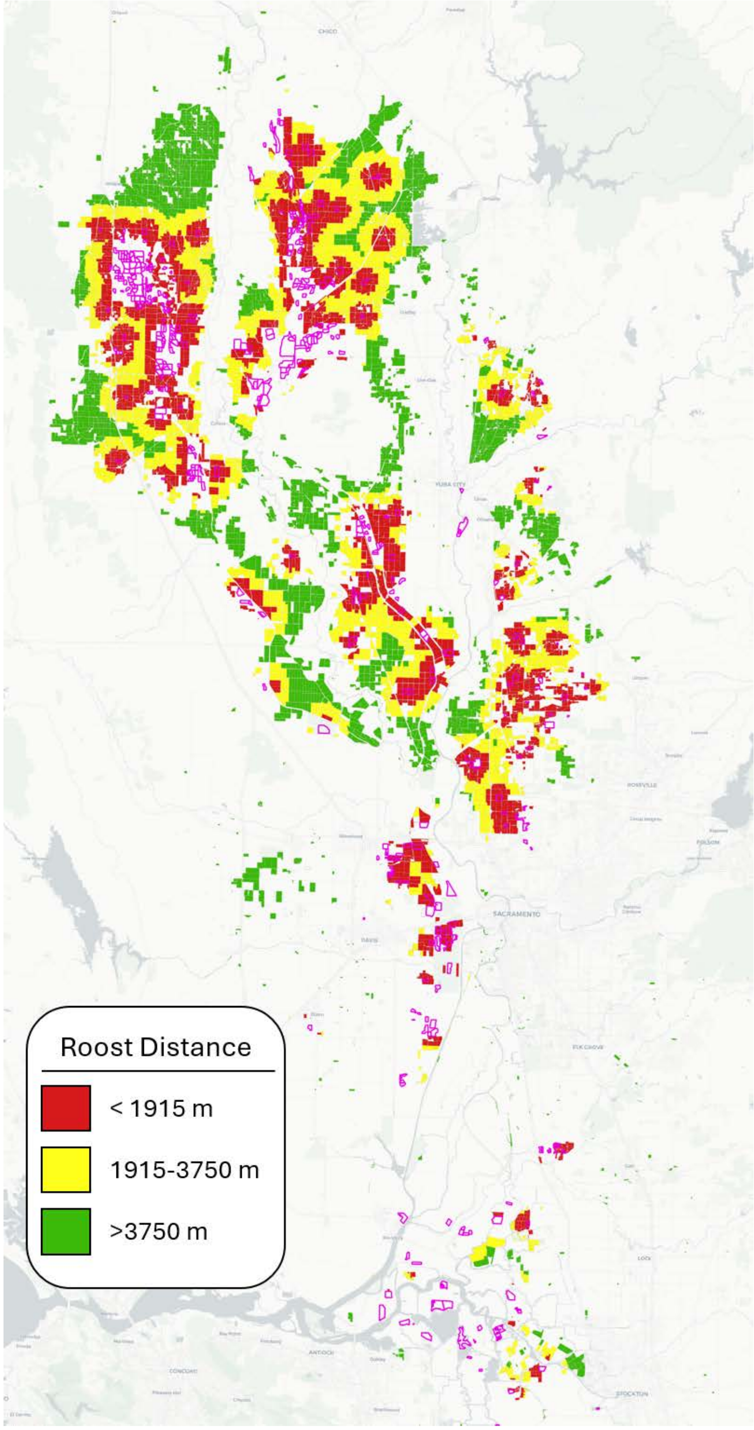


Figure 35. Rice Patches Colored by Distance to Nearest Roost

3.5.2 Duck Usage by Rice Patch

We next evaluated rice patch importance based on GIS recorded duck usage data provided by USGS, both in raw terms and basin-adjusted usage. Basin-adjusted usage accounts for variability in overall use between basins by adjusting patch-level use according to basin-level targets. This adjustment accounts for potential biases in the GIS data collection at the basin level, but not at a finer scale. As above, patches are categorized into terciles based on total rice acreage (Figure

36A), with the top third of rice acreage shown in RED (top 93% of usage, high priority), the middle tercile in yellow (~7% use), and the lowest tercile in GREEN (low priority, indicating minimal use).

Once again, the highest-priority areas were concentrated in the Butte and Colusa Basins near major refuges. Notable high-priority patches were also identified near Cosumnes in the Delta, in the Yolo Bypass, and within the lower American Basin near Sacramento Airport and northeast of Yuba City. These areas exhibited the greatest relative duck usage, highlighting their importance for conservation and habitat maintenance efforts.

In addition to the patch usage at the fine scale, we are interested in foraging area usage, as this is the level at which we have model predictions. Here we sum the patch level basin-adjusted usage by foraging area, and again present usage in terciles (Fig 36B). The top third, shown in RED accounts for 61.9% of all duck usage. The middle third, in YELLOW, accounts for an additional 29.3%, while the bottom third, in GREEN, accounts for the final 8.8% of duck usage in the dataset.

At this higher level, we see that usage priority is again concentrated near Sacramento, Delevan, and Colusa National Wildlife Refuges, as well as a large swath of Butte Basin. Additional high priority rice areas exist in the American Basin, Yolo Bypass, in Delta, particularly near the Cosumnes River Preserve. Areas in Sutter and lower Colusa have lower priority at this broader scale.

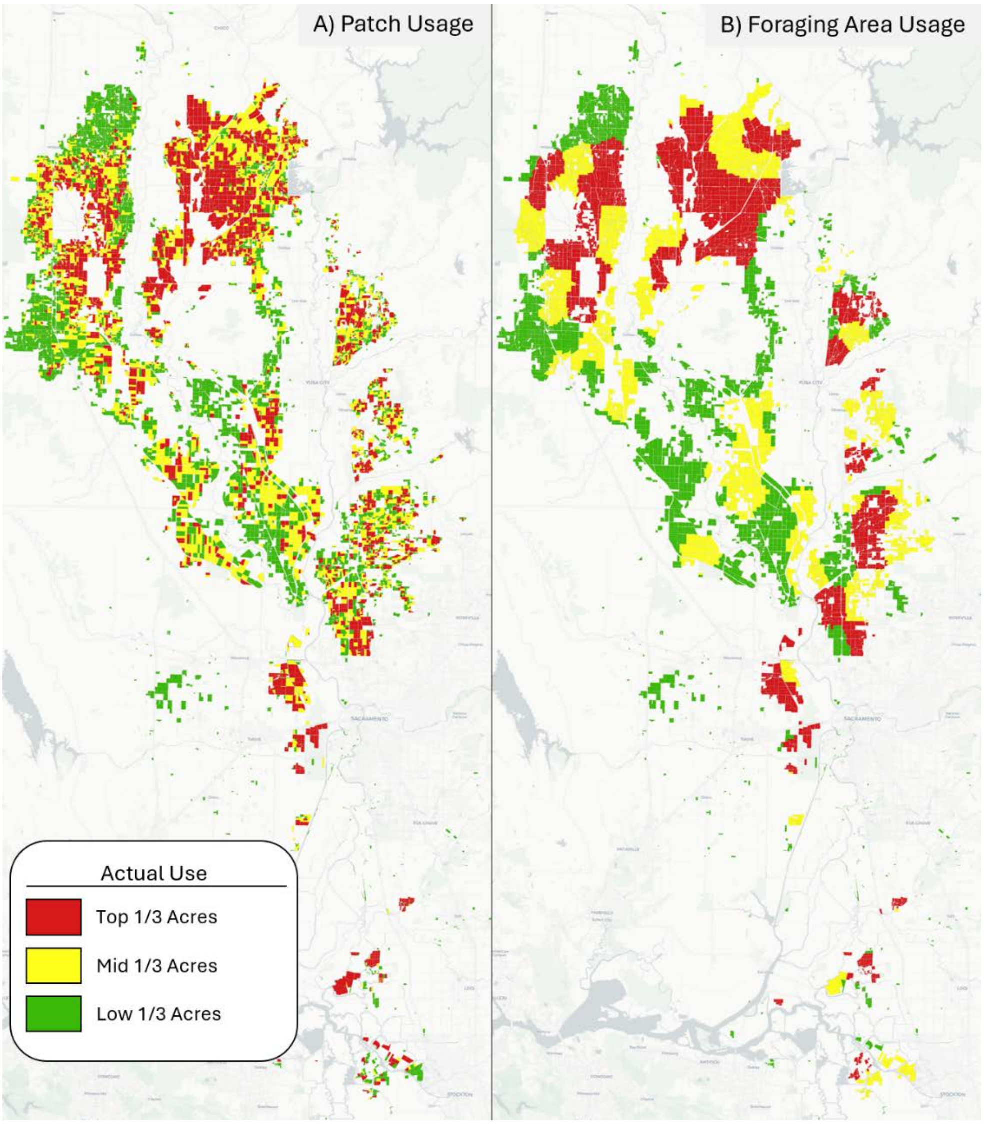


Figure 36. Rice Usage Based on GIS Data. A) Basin-Adjusted Patch Usage, B) Basin-Adjusted Foraging Area Usage

3.5.3 Model Predicted Usage Under Different Acreage Scenarios

To further understand the impact of habitat reduction or expansion, we examined predicted use for three different rice acreage scenarios representing a RED (300,000 acres), YELLOW (400,000 acres), and GREEN (500,000 acres) scenario (Figure 37). Again, priority is presented in terciles of rice acreage. The results confirm that key areas in the Colusa and Butte Basins near wildlife refuges are consistently of high importance, regardless of acreage level. Additionally, high-priority patches in Butte Basin near Nelson, near Sutter National Wildlife Refuge, and in the American Basin northeast of Yuba City and near the Sacramento airport were highlighted. These areas are pivotal in supporting the duck population during different landscape conditions.

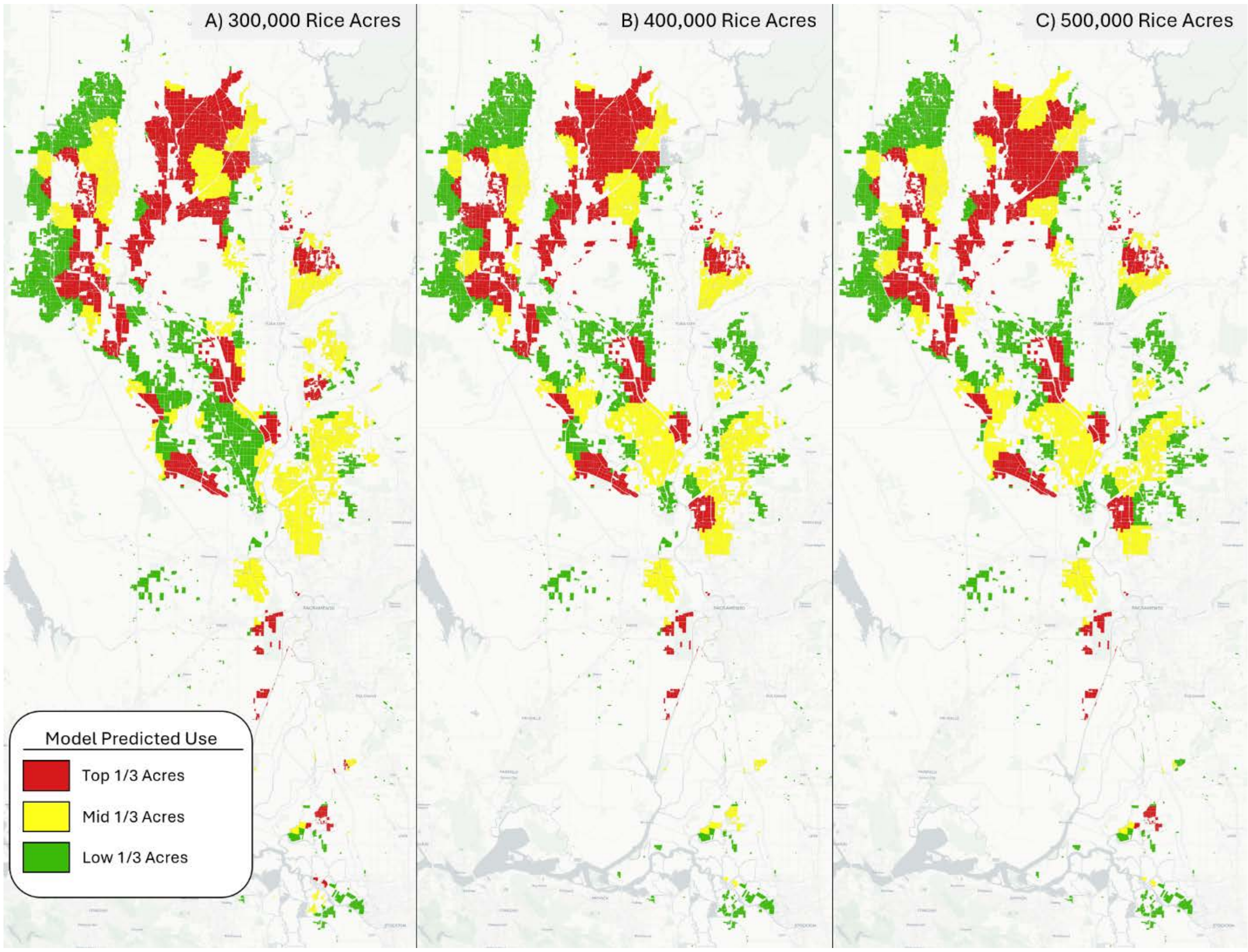


Figure 37. Rice Usage Based on Model Outputs. A) 300,000 Rice Acre Scenario, B) 400, 000, Rice Acre Scenario, C) 500,000 Rice Acre Scenario

A combined prioritization based on model-predicted usage is shown in Figure 38. Each foraging area is assigned to one of four4 categories, as follows. First, the highest priority (BLACK) areas are those which were high priority (RED) for all three rice acreage scenarios. High priority areas (RED) were high priority in at least one of the three scenarios. Medium priority areas (YELLOW) were at least medium priority in at least one of the scenarios. Low priority areas (GREEN) were low priority in all the scenarios.

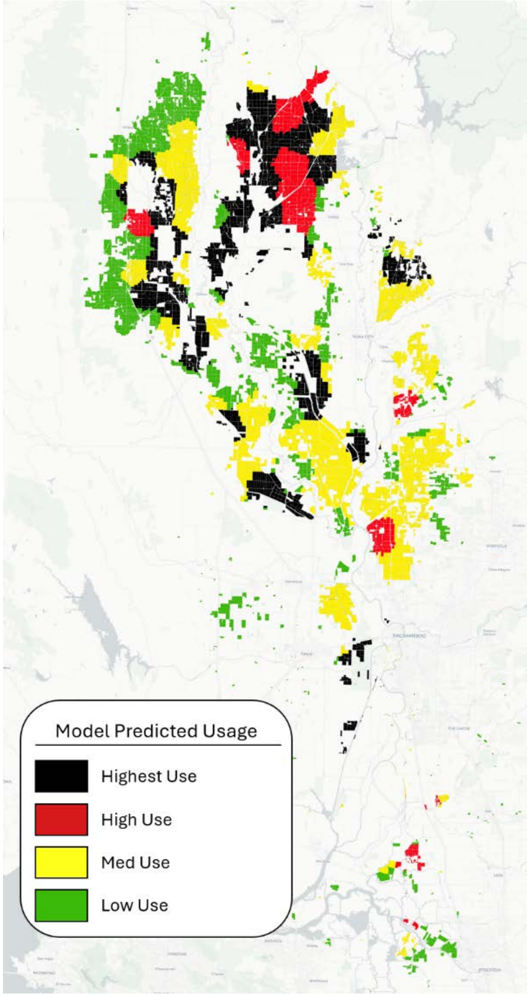


Figure 38. Priority from model predicted usage.

3.5.4 Combined Spatial Prioritization

The results of all the spatial analyses were synthesized into a Combined Spatial Prioritization map to create a composite view of rice field prioritization based on combining three priority layers: 1) Basin-Adjusted Patch Usage (Figure 36A), 2) Basin-Adjusted Foraging Area Usage (Figure 36B), and 3) Model Predicted Priority (BLACK and RED from Figure 38). The results are shown in Figure 39. Here rice patches were classified into four priority categories:

- **Priority 0 (Highest Priority)**: These patches were categorized as RED across all relevant spatial layers. They represent the most critical areas for duck foraging and roosting support. A total of 79,191 acres fall under this category, primarily in areas with high proximity to roosts and high duck usage, but also including a significant portion of the rice in Butte Basin.

- **Priority 1**: These patches were categorized as RED in at least one of the spatial maps, comprising 258,946 acres (or 338,136 acres if combined with Priority 0 areas). They represent areas of significant conservation value, albeit not as consistently prioritized as Priority 0.

- **Priority 2**: These patches were not consistently RED but were classified above low priority in at least one map. They comprise 170,060 acres and provide valuable supplemental habitat, particularly during favorable years.
- **Priority 3 (Lowest Priority)**: These patches were classified as GREEN across all previous maps. Comprising 78,220 acres, they may have lower priority in terms of conservation importance.

The Combined Spatial Prioritization map provides a valuable tool for identifying the most critical areas for habitat preservation and management under limited acreage scenarios. Priority 0 areas, although covering only about 13.5% of the total rice area, account for a disproportionately large share of duck foraging and roosting needs, containing 45.7% of all duck usage points and 44.3% of all roosting occurrences within rice. Similarly, while priority 0 and 1 areas combined account for 57.7% of rice acreage, 96.4% of use and 96.0% of roosting occurrences are contained here. This provides a strong basis for targeting these areas for future conservation efforts and water allocation, especially during drought years.

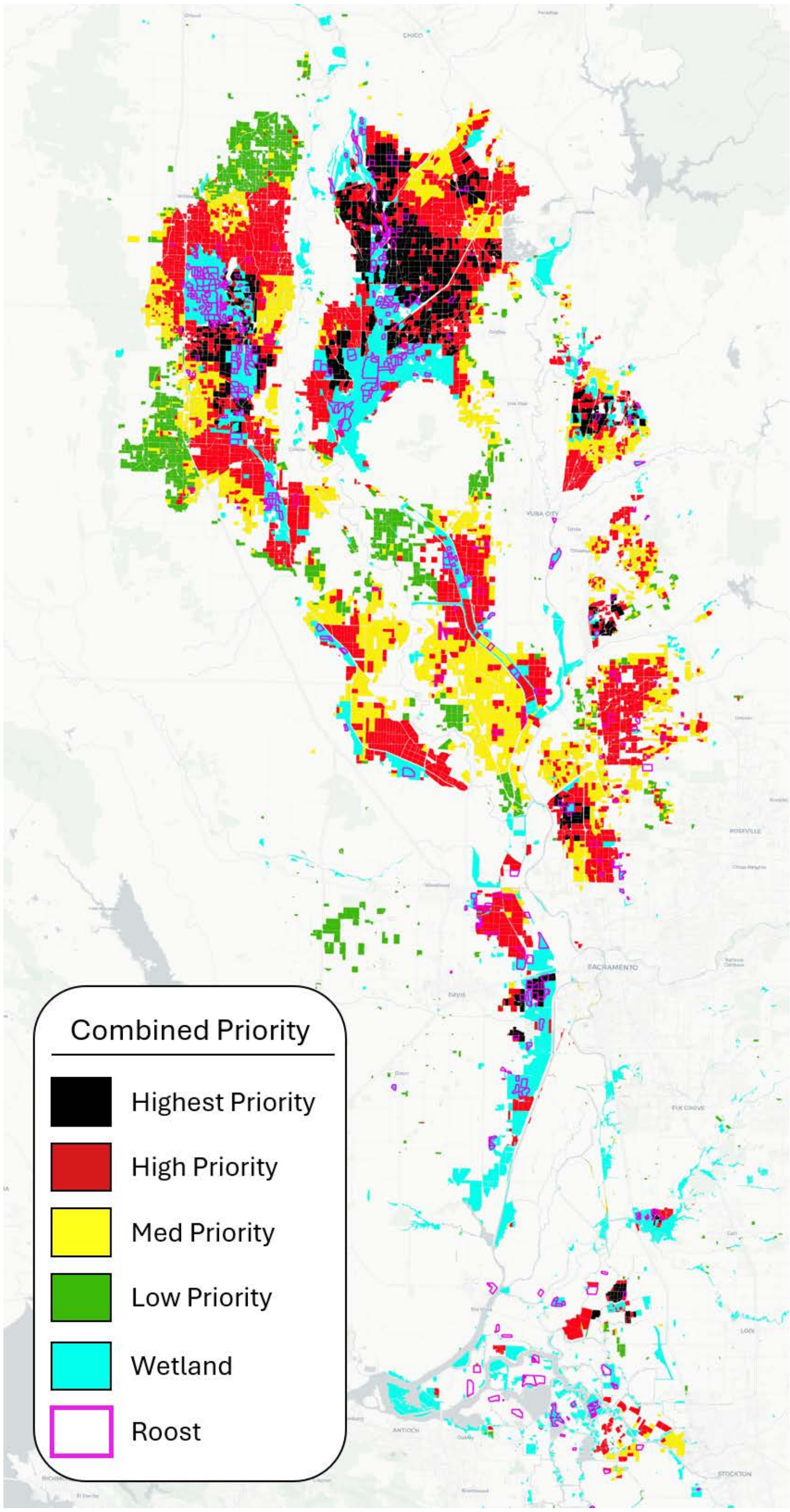


Figure 39. Combined Spatial Prioritization. Highest Priority patches are Red in ALL previous spatial maps, High Priority patches were Red in at least 1 of the previous spatial maps. Low Priority were Green in all the previous maps. All other patches are Med Priority.

3.5.5 Implications for Future Modeling and Management

The combined spatial prioritization provides a baseline from which to build and refine scenarios for more in-depth modeling. The prioritization scheme is particularly useful for guiding water allocation decisions during drought years, as it helps to identify which areas are most critical to maintaining habitat availability. Future research should focus on testing the efficacy of these spatial priorities under real-world conditions and refining the metrics based on additional data.

This approach also underscores the importance of targeted, spatially efficient conservation actions. By concentrating management efforts on high-priority patches, managers can achieve substantial ecological benefits even under constrained resource conditions. Such spatial prioritization will be crucial for sustaining duck populations in California's Central Valley amid fluctuating water availability and changing agricultural practices.

3.6 Summary of Findings

The results from the simulation experiments highlight the critical role of habitat availability, population dynamics, and competition management in sustaining duck populations in California's Central Valley. Key findings include:

- **Impact of Goose Competition**: Goose competition, particularly in the Goose100 treatment, significantly reduces the ability of the landscape to sustain duck populations. Reducing goose energy removal, as seen in the Goose75 and GooseScaled treatments, provided a buffer that extended population viability and improved energy balance, particularly in challenging habitat years. Experiment 3 further emphasized that reducing interspecific competition through less aggressive goose scenarios allowed the landscape to support duck populations at lower rice acreages.

- **Population Viability and Habitat Sufficiency**: In favorable years like 2021 and 2324, the landscape was able to sustain duck populations near target levels throughout most of the winter season, even under high goose competition. However, in years with reduced rice and wetland acreage, such as 2223 and 2223NR, population declines occurred earlier and more precipitously, especially under high competition. The SV population chronology in Experiment 2 demonstrated that the landscape could better sustain early-season population pressure than late-season peaks. Experiment 3 showed that while population viability was feasible under varying rice acreage conditions, the threshold for sustainability depended heavily on competition levels and population timing.

- **Rice Acreage Threshold for Sustainability**: Experiment 3 identified the minimum acreage of rice fields needed to sustain wintering duck populations under both demanding (Goose100 and SVDelayed) and less-demanding (GooseScaled and SV) conditions. The results showed that population health metrics, such as Days to Deficit, Day Population Falls Below 50% of Target, and Total Duck Use Days, generally reached an asymptote around 500,000 acres of rice, indicating that above this threshold, additional acreage provided little added benefit. Under less demanding conditions, however, sustainable outcomes were achievable with as low as 375,000-400,000 acres of rice. This suggest that while maintaining 500,000 acres of rice would be ideal, lower acreages may suffice when conditions are less favorable.

- **Timing of Resource Shortages**: Energy Demand Days Remaining (EDDR) and Daily Net Energy Balance metrics showed that critical resource shortages occurred earlier in challenging scenarios, particularly under Goose100. Goose75 and GooseScaled treatments helped delay these shortages, extending the period during which the landscape could support the population. In Experiment 2, the SVExtended chronology experienced earlier resource limitations compared to SVDelayed, JVTarget, and SV, which had better late-season habitat sufficiency. Experiment 3 confirmed that increasing rice acreage significantly delayed these resource shortages, with demanding conditions requiring more acreage to maintain a positive energy balance late into the season.

- **Lipid Reserves and Energy Balance**: Ducks in favorable scenarios were able to build and maintain lipid reserves, while those in challenging scenarios experienced earlier declines. Goose75 and GooseScaled treatments helped ducks maintain higher lipid reserves, reducing mortality risk during late winter. In Experiment 2, the SV chronology maintained better body condition throughout the late season, emphasizing the importance of population timing on energy dynamics. Experiment 3 further showed that lipid reserve levels depended on rice acreage, with a clear benefit to increasing acreage up to approximately 500,000 acres to sustain energy reserves under demanding conditions.

- **Management Recommendations**: Based on the simulation results, it is estimated that maintaining at least 400,000-500,000 acres of rice fields (with at least 222,000 of this being available to ducks through winter flooding), combined with sufficient managed wetland acreage, is necessary to support target duck populations throughout the winter season. While maintaining 500,000 acres would ensure sustainability under challenging conditions, lower thresholds (e.g., 375,000-400,000 acres) may be sufficient under less demanding conditions. Management efforts should prioritize maintaining and optimizing the distribution of flooded habitat, particularly during critical periods of the winter season, to balance agricultural production with effective waterfowl conservation. Given the variability in water availability, adaptive strategies are needed to allocate water resources efficiently to maintain habitat quality during drought conditions while supporting both duck and goose populations. Additionally, the provided metrics offer valuable insights into the trade-offs associated with different acreage levels, allowing stakeholders to make informed decisions based on conservation goals and resource constraints.

A3. Additional Methods for Black Tern and Shorebirds

Kristen E. Dybala, Point Blue Conservation Science

From the spatial dataset described in Section 4, we extracted parcels with suitable land cover classifications for Black Tern and shorebirds in any of the 4 water years. During the peak of the breeding season (mid-April – mid-July), suitable land cover classes included permanent/semi-permanent managed wetlands and planted rice. During the nonbreeding season (1-July – 15-May), suitable land cover classes included seasonal managed wetlands, permanent/semi-permanent managed wetlands, rice (including fallowed rice fields), corn, and other annual crops that may be flooded. The dataset did not distinguish seasonal managed wetlands from permanent/semi-permanent managed wetlands, and we assumed managed wetland parcels that were more than 50% flooded in any of May, June, or July in all 3 summers for which we had complete data (2021, 2022, and 2023) were permanent/semi-permanent managed wetlands.

For the bioenergetics model, we evaluated the daily changes in the extent of flooding in each land cover class in each scenario. We assumed the monthly values provided for each parcel in each scenario represented the extent of flooding at the midpoint of each month. We then used simple linear interpolation to fill daily values between each pair of data points and assumed no change between July 1 and July 15 at the start of each water year. Data were lacking for July-August 2020 and Apr-May 2024, when suitable habitat is primarily provided by managed wetlands, so we filled in these time frames using estimates for the same managed wetland parcels from July-August 2021 and Apr-May 2021, respectively. From these estimates of the daily extent of flooding in each parcel, we calculated the daily change in the extent of open water across all parcels in each land cover class to track both the extent of newly flooded habitat and the extent of previously-flooded habitat that has gone dry each day.

To this flooding data, we applied the original assumptions used in analyses conducted for the Central Valley Joint Venture's implementation plan for the energy content per flooded acre in each land cover class, the daily proportion of that food supply that is in shallow-flooded areas accessible to most shorebirds (<10 cm depth), and the daily energy required by the shorebird community (Dybala et al. 2017). As in the original analyses, agricultural land cover types are assumed to be inaccessible to shorebirds prior to September 1, although this assumption likely excludes some accessible habitat provided by rice and fallowed rice through incentive programs (Golet et al. 2022). We also assumed any flooded agriculture is inaccessible to shorebirds after April 1. The total daily energy requirements vary with the abundance and species composition of the shorebird community throughout the season, and here we used the daily energy requirements estimated to meet the long-term population objectives for shorebirds (Dybala et al. 2017). However, because the spatial dataset used in this analysis excluded the San Joaquin and Tulare planning regions, we downscaled these energy needs by assuming approximately 80% of the habitat and energy supply should be provided by the Sacramento and Yolo-Delta planning regions (Dybala et al. 2017).

The model's structure and parameterization were described in detail by Dybala et al. (2017), but briefly, the full energy content for a given land cover type becomes available as soon as a new area is flooded. However, only a proportion of that full energy supply is accessible to shorebirds each day, from which the shorebird community attempts to consume their daily energy requirement. An energy shortfall is recorded when the daily energy requirement exceeds the accessible energy supply, but this deficit is not carried forward. Due to insufficient data, there is no attempt to represent change in the energy supply from the growth, reproduction, or decay of the benthic invertebrates, and no attempt to account for the cost of movement between habitat patches.

A4. Sandhill Cranes

Robert G. Walsh, Point Blue Conservation Science

The Veloz et al. (2017) model of crane roost suitability was developed based on a specific set of roosts found over a period of about ten years prior to publication. We tested whether it ranked roosts discovered after this time (and therefore not used in model development) more highly than expected by chance, which would suggest roost occurrence overlapped with areas ranked high in terms of roost suitability. This was found to be the case, supporting use of the model.

Table A5.1. Summary statistics for suitability ratings of pixels with crane roosts from Veloz et al. (2017), new roosts (i.e. not used in the model), or randomly selected points in the landscape.

Type	**N =**	**Mean Score**	**SD**	**Lower 95% CL**	**Upper 95% CL**	**Lower 95% Boot CL**	**Upper 95% Boot CL**
Known roosts (used to build model)	143	0.363	0.19	0.332	0.394	0.334	0.393
New roosts (not used to build model)	30	0.259	0.151	0.202	0.316	0.204	0.31
Random landscape pixels	1000	0.043	0.087	0.038	0.048	0.037	0.048

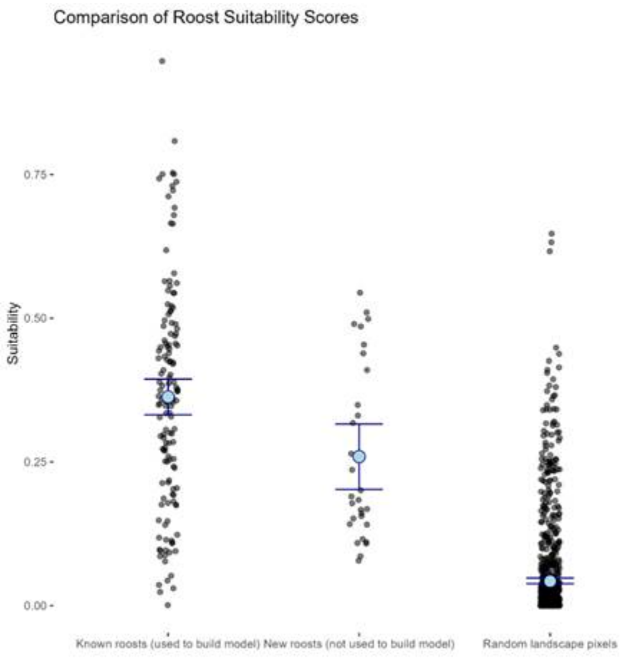


Figure A4.1. Suitability scores of crane roosts and randomly selected pixels in the landscape. Each dot represents one roost or one random point. The mean and 95% confidence intervals are overlaid.

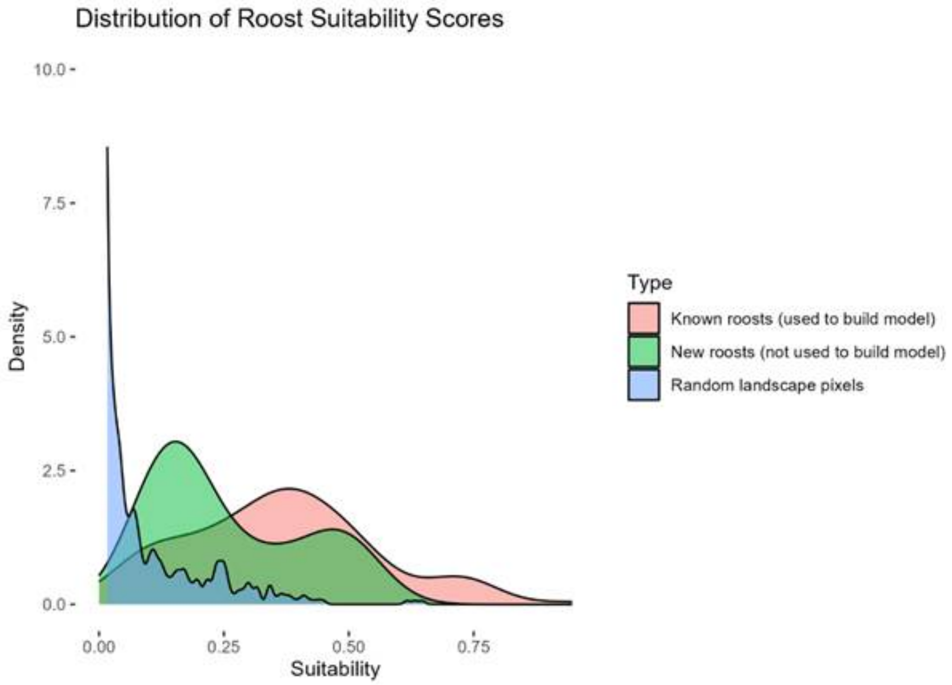


Figure A4.2. Distribution of roost suitability scores; these are the same data as in Fig. A1, presented to highlight how few randomly selected points in the landscape have high suitability scores.