To: Reclamation District 108

From: Ducks Unlimited Inc.

Date: 3/12/2024

Floodplains Reimagined

Baseline Estimations of Waterfowl Bioenergetics and Carrying Capacity

Introduction

Proposed project

The Floodplains Reimagined Project being led by RD 108 seeks to advance floodplain reactivation in a 77,507-hectare project area that includes the Butte Sink, Colusa Drain, and Sutter Bypass to benefit anadromous fish, wildlife, and people. Project objectives include enhancing floodplain functional connectivity for fish and birds while respecting existing land uses, local communities, and culture. The project area contains approximately 22,705 hectares of managed wetlands, or 27% of the managed wetlands in the Central Valley (Reid et al 2018), as well as 54,802 hectares of rice agriculture. This region supports approximately 50% of all ducks and nearly all the geese in the Central Valley, making it one of the most important regions in the Central Valley. One potential impact of floodplain reactivation is changing water depth and duration within managed wetland and rice fields, such that food resources become inaccessible to non-breeding waterfowl. The loss of access to food resources within these habitats will reduce the overall abundance of waterfowl within the project area, requiring birds to redistribute to other areas in the Central Valley to locate food resources. However, other subregions available are unlikely to have the surplus of energetic resources required to support these displaced waterfowl.

Waterfowl conservation

The successful conservation of migratory waterfowl requires coordination between multiple governments and conservation organizations to ensure populations are protected and suitable habitat is present along migratory routes which often cross international boarders (Nichols et al. 1995). In addition to protections provided under the Migratory Bird Treaty Act of 1918, the management of North American waterfowl populations is led by the North American Waterfowl Management Plan (NAWMP). Jointly signed by Canada, the United States, and Mexico to address declining waterfowl populations, NAWMP sets continental habitat restoration and population goals (NAWMP 1986). To facilitate achieving these goals, NAWMP provides regional coordination through Joint Ventures, which aid in collaborative efforts between governmental agencies and private organizations to focus on key habitat needs in each region. Management of non-breeding waterfowl has been centered around the food limitation hypothesis, which states that waterfowl abundances are influenced by food resources (Williams et al 2014). Primary support for this hypothesis has been research indicating limited food resources can directly influence waterfowl survival and habitat use, and indirectly impact reproductive success due to a lack of lipid reserves in late winter or early spring (Dubovsky and Kaminski 1994; Devries et al. 2008; Sedinger and Alisauskas 2014). Therefore, many areas that support non-breeding waterfowl have focused on the production of waterfowl food resources to aid in the recovery and preservation of waterfowl populations (Baldassarre and Bolen 2006; CVJV 2006; NAWMP 2012).

Importance of the project area to waterfowl

The Central Valley provides critical non-breeding habitat to over a dozen duck and goose species (CVJV 2020). Despite the loss of more than 90% of the historical wetland habitat the Central Valley continues to support approximately 7.5 million migratory waterfowl, nearly 60% of the Pacific Flyway, during the peak of non-breeding season (Heitmeyer et al. 1989; Gilmer et al. 1982). The ability of the Central Valley to remain a core non-breeding area is due to the conservation, restoration, and management of the current wetland habitats and wildlife friendly agriculture. The primary habitat types that support non-breeding waterfowl in the Central Valley are managed seasonal wetlands, and winter flooded rice (CVJV 2020). Seeds are a primary source of food for waterfowl in the non-breeding season, however diets shift to include more invertebrates as spring approaches (Fredrickson and Taylor 1982; Euliss and Harris 1987; Heitmeyer 1989). Managed seasonal wetlands provide waterfowl access to annual plant seeds and invertebrates, while postharvest rice fields provide waste grain and invertebrates once flooded.

Currently, winter flooded rice contributes an estimated 52% of the total food energy present for waterfowl in the Central Valley (CVJV 2020). Approximately 130,000 hectares of rice fields are flooded in winter – the majority occurring within the Sacramento Valley – following rice harvest to allow rice straw to decompose while simultaneously providing waterfowl access to waste grain that is left in the fields. Managed seasonal wetlands provide waterfowl with higher densities of food items, primarily moist-soil seeds, than winter flooded rice fields (Naylor 2002; Matthews et al. 2023). Additionally, the moist-soil seeds produced in managed wetlands contain essential nutritional components needed by waterfowl that agricultural grains lack (Fredrickson and Reid 1988). These managed wetlands cover approximately 83,000 hectares in the Central valley, two-thirds of which are privately owned and are often managed for waterfowl hunting also support shorebirds, waterbirds, and other wetland-dependent species (Reid et al. 2018; CVJV 2020).

Water depth is a critical component of wetland management as it is correlated with waterfowl use (Safran et al. 1997; Colwell and Taft 2000; Taft et al. 2002; Baschuk et al. 2011). The ability of dabbling ducks to access food resources is constrained by foraging behavior and physical constraints (Santamaría and Rodríquez-Gironés 2002; Hagy et al. 2010). The majority of waterfowl using managed wetlands in the Central Valley are dabbling ducks, such as Mallards, Northern Pintail, and Green-winged Teal. Dabbling duck species typically forage by tip-up behavior, where physical constraints such as neck length, body size, and bill length, limit their ability to access foods on the substrate of a flooded wetland. If water is too deep, dabbling ducks are unable to reach the bottom of a wetland, and therefore cannot access all the food resources. Ideal water depths for waterfowl in managed wetlands range from 5 to 25 centimeters (Fredrickson and Reid 1988; Colwell and Taft 2000; Taft et al. 2002). Although dabbling ducks will use wetlands that are deeper than 25cm, the value of these areas is primarily for loafing. Therefore, wetland managers must maintain shallow depths over the wintering period to ensure waterfowl can access the food resources in both seasonal wetlands and flooded agricultural fields.

The Central Valley Joint Venture, in collaboration with researchers, has conducted evaluations of waterfowl and their habitats to develop a bioenergetic modeling approach to assist in conservation planning within each of the five planning regions (Heitmeyer 1989; Miller and Newton 1999; Fleskes et al. 2000; Naylor 2002). Bioenergetic models evaluate if the total available food resources (energy supply) are sufficient to meet the energetic needs of a population (Goss-Custard et al. 2002; Miller et al. 2014; Williams et al. 2014). To determine the impacts that natural flooding events have on non-breeding waterfowl within the project area we used the bioenergetic model TRUEMET (Petrie et al. 2016; CVJV 2020, Petrie et al. in prep) in five baseline years (2003, 2011, 2013, 2015, 2019; see Hydrodynamic Modeling Memorandum, Appendix 5). This bioenergetic approach evaluates how changing water depth over the winter period influences the ability of waterfowl to access food resources, and as a result, how the carrying capacity of the project region will change over time due to flooding events.

TRUEMET Model structure

TRUEMET is a daily ration model that examines how a given area's energetic supply and population energetic demands change over time. TRUEMET has been utilized for planning documents in three Joint Ventures (Central Valley, Prairie Habitat, and Intermountain West), and used to examine the effects of drought (Petrie et al. 2016). Key inputs required by TRUEMET to evaluate energy supply are total habitat area and food density (calories per unit area), while energy demand is determined by daily energy requirements for a given waterfowl population. In addition to these variables, other parameters included within the model are foraging behaviors (consumption rates, foraging preferences, giving-up densities), background rates of food decomposition, and regeneration. The model relies on data provided in two-week intervals; however, values are treated as continuous over time, and inputs are interpolated over time based on calculated splines within the model. A total of 15 time-steps were examined in our analysis, each time-step is two weeks long, starting on August 23, ending on March 21. As the Floodplains Reimagined project area falls within the Sacramento Planning Basin, which was evaluated by the CVJV 2020 implementation plan using TRUEMET, many of the variables used to apply TRUEMET to the Floodplains Reimagined project area were stepped down from the CVJV TRUEMET model.

Estimating supply

We used hydrological modeling data provided by cbec to determine the total area accessible to waterfowl in the project area for each of the five baseline years (Appendix 5). Daily total areas (in hectares) of dry rice, flooded managed wetlands and winter flooded rice (to a depth less than 12 inches) were provided for each subregion (Butte, Colusa, Sutter). We summed these daily areal values across all subregions by habitat type, then averaged these values over two-week time periods to determine the total area of each habitat type within the project area for each of the 15 time-steps modeled (late August to late March). Flooded rice fields that became dry after November 21 were considered to have little to no foraging value for geese as foraging likely reduced food resources significantly and were excluded from the model (Greer et al. 2009). As the hydrological model produced values starting October 1, we used rates of flood-up from the 2006 implementation plan (CVJV 2006) to estimate the area for each habitat type during the first three time-steps (8/23, 9/7, and 9/22) based on the total area of each habitat type within the project area. We chose to include estimated values for these first three time-steps to highlight the impact of the fall flood-up period on the total energy supply.

Table 1. Average food densities and total metabolizable energy (TME) of the primary waterfowl foods within the project area.

Food Resource	Food Density (kg/ha)	TME (Kcal/g)
Moist-soil Seeds	556	2.5
Invertebrates	32	2.39
Rice	304	3

Table 2. Total accessible area (hectares) of each foraging habitat type (Rice and Managed seasonal wetlands) by subregion.

Subregion	Accessible Area (ha)	
	Rice	Managed Wetlands
Butte	27,202	14,671
Colusa	10,118	7,139
Sutter	480	1,097
Project Area	37,800	22,908

The total available energy within each habitat type was estimated by multiplying previously published values of food densities by their metabolizable energy, or the energy that waterfowl gain from consuming a given mass of that food item (Table 1) (Naylor 2002; CVJV 2020). Similarly, the rates at which moist-soil seeds and waste grains decompose over time were included in the model as background rates of energy loss not attributable to waterfowl (Naylor et al. 2002; Nelms and Twedt 1996). Invertebrate abundance was modeled for managed wetlands, with production occurring starting January 1. Invertebrate densities were assumed to be limited to 31 kg/ha, but regeneration rates of invertebrate were included, with an average rate of 0.186 g/m^2 per day (Manley 1999; Hohman et al. 1999; Moss et al. 2009). The presence of waste corn available to waterfowl within the project region is likely negligible and was therefore not included in the model.

Estimating demand

Three foragers were modeled, dabbling ducks, geese, and swans. We chose to combine geese and swans based on the CVJV 2020 approach, resulting in two forager types being included in the TRUEMET model. Each of the forager type was assigned unique values within the bioenergetic model, including foraging preferences (foraging habitat selection), daily energetic demands, and changes in abundance over time. We applied the foraging preference assumptions utilized by the CVJV 2020 implementation plan, where geese/swans only forage in dry or flooded rice fields, while dabbling ducks forage in wetlands and flooded rice fields.

Daily energy requirements for each forager type were informed by the CVJV 2006 plan, which reflect the variation in total energetic demands at each time step (CVJV 2006). Energetic demands for dark geese, light geese, and swans were averaged for each time step, based on the proportional abundance based on population estimates. Total population sizes were estimated every two weeks by stepping down population trends presented by the CVJV 2006 plan in the Butte, Colusa, and Sutter basins (Fig. 1 and Fig. 2). To determine the proportion of Sacramento Basin waterfowl likely to occur within the project area, we estimated the total abundance of each forager type based on the total energy available in each habitat type (Table 2) present in the project area and compared the calories present in the project area compared to the Sacramento Basin in the CVJV 2020 plan (Fig. 3). Overall, the project area contains over a third (39.3%) of the total energy available to wintering waterfowl present in the entire Sacramento Planning basin. Due to foraging preferences, we estimated that the project area will support approximately 42% of the ducks, and 29% of the geese that overwinter in the Sacramento Basin (Fig. 3).

Table 3. The daily energy requirements for ducks, and white and dark geese over the wintering period in the Central Valley. Data from the CVJV 2006 implementation plan.

Date	Duck DER (Kcal/day)	White goose DER (Kcal/day)	Dark goose DER (Kcal/day)
23-Aug	194	0	0
7-Sep	194	0	0
22-Sep	236	499	522
7-Oct	231	499	522
22-Oct	231	632	522
6-Nov	233	632	538
21-Nov	21	636	538
6-Dec	208	635	544
21-Dec	218	622	540
5-Jan	218	575	497
20-Jan	260	557	498
4-Feb	260	541	553
19-Feb	224	525	553
6-Mar	224	520	549
21-Mar	224	503	538

Total Available Energy Assessment

In addition to our full TRUEMET evaluation that examined energy supply and demand, we also conducted a simplified examination of the total number of kilocalories that were available to waterfowl within each subregion for each of the five baseline years. We used TRUEMET – informed by data on the total area available to waterfowl as estimated by the hydraulic models produced by cbec – to estimate the total available energy over the wintering period (8/23 – 3/21) in the absence of waterfowl. To match our approach with the full TRUEMET analysis; we estimated the area for each habitat type for the three timesteps (8/23, 9/7, 9/22) that precede the hydrological model outputs using the habitat curves from the Sacramento Valley in the CVJV 2006 implementation plan (CVJV 2006) and assumed dry rice entering the model after Nov. 21 would have no food value. This approach accounted for depletion and changing water depths which reduced the daily energy supply accessible to waterfowl. We summed the total energy available for each day across the entire wintering period (8/23 – 3/21) to produce subregion specific annual totals. This total available energy assessment allows for a quick comparison across subregions and years to better evaluate how flooding impacts waterfowls access to energy resources. Although this approach does not serve as a method to estimate the number of waterfowl an area could support, it allows us to infer how variable water depths within each subregion, for each year, mediate the total energy available to waterfowl.

Results

TRUEMET bioenergetics

The availability of each habitat type was similar for each of the five years examined through the first 75 days of the wintering period (Aug. 23 - Nov. 6), after which, variable water depth modified the total area available to waterfowl (Fig. 4). This change in habitat availability corresponds to the TRUEMET bioenergetic model outputs that show peak food abundance for waterfowl typically occurred in the first week of October (Fig. 5). This period of abundant food resources was also due to food resources having been exposed to minimal levels of depletion and decomposition. Food resources are quickly depleted between the end of October and late December, as waterfowl numbers begin to peak (Fig. 3), and no additional food resources enter the system. Further reductions in available energy due to reduced area occurred in 2013 and 2015, between Early December and January (Fig.4 and 5). Energy available from rice – both winter flooded and dry fields – is quickly depleted in all years and exhausted by December 21. The overall contribution of energy from invertebrate food sources was minor compared to seed sources. Total food resources become sparse in late January for nearly all baseline years (Fig. 6). Energy demand exceeded the available energy supply in one baseline year (2019), indicating waterfowl would need to leave the project area to acquire food. Overall, our model results indicate that under baseline conditions, waterfowl populations can be limited by a lack of food resources under natural flooding events.

The increase observed in the available energy supply during late December or early January in 2013 and 2015 is the result of an increase in available flood rice area. This increase in flood rice acreage is likely due to deeply flooded fields returning to depths that waterfowl can access. However, the structure of TRUEMET assigns these areas food density values as if they experienced no depletion or decomposition, which likely overestimates the energy supply available in these fields unless previously unflooded rice fields are becoming flooded for the first time.

Total available energy

The total energy available to waterfowl in each subregion is heavily dependent on the total area of each subregion, with Butte providing the most available energy, and Sutter provided the least. (Table 4). Our approach of inferring cover area availability for each habitat type (dry rice, flooded rice, and managed wetlands) between August 23 – Sept 30 based on the 2006 CVJV flood schedules accounted for approximately 7% of the total energy. The least energy available to waterfowl for all subregions occurred in 2019, resulting in the project area providing approximately 10 % less total energy when compared to the mean. The highest total energy values occurred in 2011 for Colusa and Sutter, while 2003 resulted in the highest total energy value for Butte. The largest proportional difference between the year that provided the most and least energy occurred in the Sutter subregion, in which 20% more in energy was available in 2011 compared to 2019. Colusa supplied to most consistent available energy, and smallest yearly difference in total available energy occurred in Colusa, which had a coefficient of variation of 0.033 (Table 4).

Table 4. Mean, median, and coefficient of variation in the annual total available energy (Gcal) within each subregion over the five baseline years (2003, 2011, 2013, 2015, 2019) during the wintering period (8/23 – 3/21).

Subregion	Mean	Median	CV
Butte	3,862,408	3,870,029	0.044
Colusa	1,638,975	1,663,054	0.033
Sutter	160,342	167,357	0.079
Project Area	5,661,724	5,709,320	0.038

Table 5. Summed daily energy (Gcal) available to waterfowl over the wintering period (8/23 – 3/21), by each subregion over the five baseline years (2003, 2011, 2013, 2015, 2019).

Subregion	Energy (Gigacalories)				
	2003	*2011*	*2013*	*2015*	*2019*
Butte	4,030,425	4,027,240	3,821,697	3,870,029	3,562,647
Colusa	1,599,535	1,706,727	1,663,054	1,668,754	1,556,806
Sutter	145,655	173,901	167,357	170,537	144,258
Project Area	5,775,615	5,907,868	5,652,108	5,709,320	5,263,710

Conclusions and future considerations

Our model results provide a benchmark estimate of how flooding can impact access to the food resources needed by non-breeding waterfowl under a variety of different water years. We found that waterfowl populations can be limited by reduced access to food resources caused by natural flooding events. This was in contrast to the bioenergetic modeling results presenting in the CVJV 2020 Implementation Plan, likely due to the assumption that all habitats would remain available after initial flooding. By including data produce by the hydraulic model that demonstrated a loss of waterfowl foraging habitat due to increase water depths, we found waterfowl populations did not have access to sufficient food resources in certain years. Moreover, we found that energetic resources within both dry and winter flooded rice fields were exhausted by mid-December in all five baseline years (Fig. 5), indicating that waterfowl populations rely solely on managed seasonal wetlands after mid-December. Therefore, waterfowl populations are at risk of not having sufficient access to required energy supplies if managed wetlands become deeply flooded during late winter and early spring. We observed this in 2019, when the total area of managed wetlands accessible to waterfowl declined by approximately 50% after January, resulting in total energy demand exceeding the available energy supply (Fig. 6). A lack of food resources within the project area is likely to result waterfowl being forced to leave or experience a decline in body condition due to insufficient energy intake. Although a decline in body condition – a reduction in lipid reserves – may not immediately result in waterfowl mortality, future waterfowl production can be impacted (Heitmeyer and Fredrickson 1981; Anteau and Afton 2009; Guillemain et al. 2008). Furthermore, waterfowl leaving the project area to locate food resources will increase the total energetic demand on adjacent wetland areas which may not have a sufficient surplus of energy to support additional birds. The high densities of waterfowl foods in managed seasonal wetlands are the result of extensive management, and passively managed wetlands that may become available during occasional flood events will likely provide significantly less food to waterfowl (Brasher et al. 2007; Stafford et al. 2011).

Our examination of total energy provided insight into how natural flooding events influence food availability at the subregion level across the five baseline years (Table 5). These total energy values cannot be converted into reliable estimates of the total number of waterfowl a subregion could support over the wintering period due to the lack of accounting for depletion, instead they serve as a metric to compare differences in the size of waterfowl energetic supplies between subregions and years. We found the total available energy provided by Colusa subregion was the more consistent across years, with a coefficient of variation of 0.033, compared to the other subregions (Table 4). Conversely, available energy within Sutter subregion was more varied across years, with a coefficient of variation of 0.079. The year 2011 provided the most energy within the project area, which corresponded with peak available energy in both Colusa and Sutter. Interestingly, peak available energy occurred in 2003 for Butte, suggesting flooding in 2003 reduced energy accessibility in Colusa and Sutter to a greater extent. All subregions provided the least available energy in 2019. This decline in available energy in 2019 corresponded with our TRUMET evaluation, in which the energetic demand of waterfowl exceeded the available supply.

We chose to exclude unmanaged areas from our analysis due to these areas likely providing sub-optimal forage, infrequently. Unmanaged wetland areas, or areas that are not purposefully flooded and only become flooded occasionally provide less food resources to waterfowl than intensively managed wetlands (Brasher et al. 2007; Stafford et al. 2011). The exception to this would be unmanaged rice fields (fields not intended to be flooded in winter), which do hold high densities of food resources and can hold shallow water for short periods of time in certain years when heavy rainfall occurs. However, these unflooded fields typically have lower densities of waste grain by the time flooding occurs, likely due to other granivores depleting resources prior to flooding (Matthews et al. 2022). Therefore, we assumed these areas provided little to no food for dabbling and excluded them from our analysis. Future evaluations could provide additional insight into how important these areas are for geese within the project area.

Our model may overestimate the energy available in managed wetlands and winter flooded rice after flooding events due to how variable water depths are considered. Currently, the model allows for newly accessible areas enter at any period, potentially adding rice fields or managed wetlands that are returning to acceptable depths after being deeply flooded. These areas may have already experienced extensive foraging pressure before they became deeply flooded, and therefore have little to no food remaining. However, these areas were treated as new fields with high densities of foods. This overestimation likely occurred in 2013 and 2015, as increases in managed wetlands seeds occurred in early January (Fig. 5), after the total accessible area in managed wetlands rebounded following drop in total area in mid-December.

This analysis provided us with an opportunity to better understand how interannual variation in natural flooding influences the availability of waterfowl food resources. Prior conservation planning approaches that utilized bioenergetic models typically ignored these sources of variation, but we found that waterfowl populations can potentially face major energy shortfalls due to changes in water depth due to flooding events. Just as anthropogenic climate change has increased the frequency and intensity of droughts which can lead to a loss of food resources for waterfowl (Diffenbaugh et al. 2015; Petrie et al. 2016), increased risks of increased winter flooding may similarly reduce the availability of waterfowl foods (Swain et al. 2020, Huang and Swain 2022). A landscape-level assessment of how flooding influences the availability of waterfowl food resources within the Central Valley is needed to better understand the impact of these events. Additional insight into how waterfowl respond to flood events could be gained by incorporating location data from marked waterfowl. Future waterfowl conservation planning efforts should consider how flooding can reduce the total available area in which waterfowl can access food resources.

References

Anteau, M.J. and Afton, A.D. (2009). Lipid reserves of lesser scaup (Aythya affinis) migrating across a large landscape are consistent with the "spring condition" hypothesis. The Auk 126: 873–883.

Baldassarre, G.A. and Bolen, E.G. (2006). Waterfowl Ecology and Management. 2nd edition. Krieger Publishing Company, Malabar, FL, USA. 576 pp

Baschuk, M.S., Koper, N., Wrubleski, D.A., and Goldsborough, G. (2012). Effects of Water Depth, Cover and Food Resources on Habitat use of Marsh Birds and Waterfowl in Boreal Wetlands of Manitoba, Canada. Waterbirds, 35(1), 44–55. https://doi.org/10.1675/063.035.0105

Brasher, M.G., Steckel, J.D., Gates, R.J., and GATES, R. J. (2007). Energetic Carrying Capacity of Actively and Passively Managed Wetlands for Migrating Ducks in Ohio. Journal of Wildlife Management, 71(8), 2532–2541. https://doi.org/10.2193/2006-401

Colwell, M.A., and Taft, O.W. (2000). Water Depth predicts species use. Waterbirds, 23(1), 45–55.

[CVJV] Central Valley Joint Venture. (2006). Central Valley Joint Venture 2006 implementation plan: Sacramento, California: U.S. Fish and Wildlife Service.

[CVJV] Central Valley Joint Venture. (2020). Central Valley Joint Venture 2020 implementation plan: Sacramento, California: U.S. Fish and Wildlife Service.

Devries, J.H., Armstrong, L.M., MacFarlane, R.J., Moats, L., and Thoroughgood, P.T. (2008). Waterfowl nesting in fall-seeded and spring-seeded cropland in Saskatchewan. Journal of Wildlife Management 72: 1790–1797.

Diffenbaugh, N. S., Swain, D. L., Touma, D., and Lubchenco, J. (2015). Anthropogenic warming has increased drought risk in California. Proceedings of the National Academy of Sciences of the United States of America, 112(13), 3931–3936. https://doi.org/10.1073/pnas.1422385112

Dubovsky, J. A., and Kaminski, R. M. (1994). Potential Reproductive Consequences of Winter-Diet Restriction in Mallards. In Source: The Journal of Wildlife Management (Vol. 58, Issue 4). https://about.jstor.org/terms

Euliss, N.H., and Harris, S.W. (1987). Feeding ecology of Northern Pintails and Green-winged Teal wintering in California. Journal of Wildlife Management 51: 724–732

Fleskes, J.P., Jarvis, R.L., and Gilmer, D.S. (2002). Distribution and movements of female northern pintails radio tagged in the San Joaquin Valley, California. Journal of Wildlife Management 66:138-152.

Fredrickson, L.H., and Reid, F.A. (1988). Waterfowl Use of Wetland Complexes. Waterfowl Management Handbook. 1.

Fredrickson, L.H., and Taylor, T.S. (1982). Management of Seasonally Flooded Impoundments for Wildlife. United States Department of the Interior, Fish and Wildlife Service Resource Publication 148. Washington, District of Columbia. 29 p.

Gilmer, D.S., Miller, M.R., Bauer, R D., and LeDonne, J.R. (1982). California's Central Valley Wintering Waterfowl: Concerns and Challenges. https://digitalcommons.unl.edu/usfwspubs/41

Goss-Custard, J. D., Stillman, R. A., West, A. D., Caldow, R. W. G., and Mcgrorty, S. (2002). Carrying capacity in overwintering migratory birds. Biological Conservation, 105, 27–41. www.elsevier.com/locate/biocon

Greer, D. M., Dugger, B. D., Reinecke, K. J., and Petrie, M. J. (2009). Depletion of Rice as Food of Waterfowl Wintering in the Mississippi Alluvial Valley. Journal of Wildlife Management, 73(7), 1125–1133. https://doi.org/10.2193/2008-250

Guillemain, M., Elmberg, J., Arzel, C., Johnson, A.R. and Simon, G. (2008). The income-capital breeding dichotomy revisited: late winter body condition is related to breeding success in an income breeder. Ibis 150: 172– 176.

Hagy, H.M. (2010). Winter food and waterfowl dynamics in managed moist-soil wetlands in the Mississippi Alluvial Valley. Ph.D. thesis. Mississippi State University, Mississippi State, USA.

Heitmeyer, M. E. (1989). Agriculture/wildlife enhancement in California: The Central Valley Habitat Joint Venture. Transactions of the North American Wildlife and Natural Resources Conference 54:391-402.

Heitmeyer, M. E., D.P. Connelly, and R.L. Pederson. (1989). The Central, Imperial, and Coachella valleys of California. Pages 475-505 in L.M. Smith, R.L. Pederson, and R.M. Kaminski, editors. Habitat management for migrating and wintering waterfowl in North America. Texas Tech University Press, Cambridge, United Kingdom.

Heitmeyer, M.E. and Fredrickson, L.H. (1981). Do wetland conditions in the Mississippi Delta hardwoods influence mallard recruitment? Transactions of the North American Wildlife and Natural Resources Conferences 46: 44–57.

Heitmeyer, M.E. (1988). Body composition of female mallards in winter in relation to annual cycle events. Condor 90: 669–680.

Hohman, W. L., T. M. Stark, and J. L. Moore. (1999). Food availability and feeding preferences of breeding fulvous whistling ducks in Louisiana ricefields. Wilson Bulletin 108:137-150.

Huang, X., and Swain, D. L. (2022). Climate change is increasing the risk of a California megaflood. Science Advances, 8, 1–13.

Manley, S. W. (1999). Ecological and agricultural values of winter-flooded ricefields in Mississippi. Dissertation, Mississippi State University, Mississippi State, Mississippi, USA.

Matthews, L. J., Petrie, M., and Eadie, J. M. (2022). Impacts of Changing Postharvest Agricultural Practices on Abundance of Waste Grain in California's Central Valley. Journal of Fish and Wildlife Management, 13(2), 32–333. https://doi.org/10.3996/JFWM-21-061

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

Miller, M.R. and Newton, W.E. (1999). Population energetics of northern pintails wintering in the Sacramento Valley, California. Journal of Wildlife Management 63: 1222–1238.

Moss R.C., Blumenshine S.C., Yee J., and Fleskes, J.P. (2009). Emergent insect production in post-harvest flooded agricultural fields used by waterbirds. Wetlands, 29(3):875-883.

Murkin, H.R., Murkin, E.J., and Ball, J.P. (1997). Avian habitat selection and prairie wetland dynamics: a 10-year experiment. Ecological Applications 7: 1144-1159.

[NAWMP 1986] U.S. Department of the Interior, Environment Canada, and Environment and Natural Resources Mexico. (1986). North American Waterfowl Management Plan. U.S. Department of the Interior, Washington, D.C., USA.

[NAWMP 2012] U.S. Department of the Interior, Environment Canada, and Environment and Natural Resources Mexico. (2012). North American Waterfowl Management Plan, People conserving waterfowl and wetlands. U.S. Department of the Interior, Washington, D.C., USA.

Naylor, L.W. (2002) Evaluating moist-soil seed production and management in Central Valley Wetlands to determine habitat needs for waterfowl. M.Sc. thesis, University of California, Davis, California, USA

Nichols, J.D., Johnson, F.A., and Williams, B.K. (1995). Managing North American Waterfowl In The Face Of Uncertainty. Annual Review of Ecology, Evolution, and Systematics, 26, 177–199. https://digitalcommons.unl.edu/usfwspubs

Petrie, M. J., Fleskes, J.P., Wolder, M.A., Isola, C.R., Yarris, G.S., and Skalos, D.A. (2016). Potential effects of drought on carrying capacity for wintering waterfowl in the central valley of California. Journal of Fish and Wildlife Management, 7(2), 408–422. https://doi.org/10.3996/082015-JFWM-082

Reid, F. A., Fehringer, D., Spell, R., Petrik, K., and Petrie, M. (2018). Wetlands of California’s Central Valley (USA). In The Wetland Book II: Distribution, Description, and Conservation (Vol. 1, pp. 697–703). Springer Nature. https://doi.org/10.1007/978-94-007-4001-3_119

Safran, R.J., Isola, C.R., Colwell, M.A., and Williams, O.E. (1997). Benthic invertebrates at foraging location of nine waterbird species in managed wetlands of the northern San Joaquin Valley, California. Wetlands, 17(3), 407–415.

Santamaría, L. and Rodríguez-Gironés, M.A. (2002_. Hiding from swans: optimal burial depth of sago pondweed tubers foraged by Bewick’s swans. Journal of Ecology 90: 303–315.

Sedinger, J. S., and Alisauskas, R. T. (2014). Cross-seasonal effects and the dynamics of waterfowl populations. Wildfowl, 4, 277–304.

Stafford, J.D., Yetter, A.P., Hine, C.S., Smith, R.V., and Horath, M.M. (2011). Seed abundance for waterfowl in wetlands managed by the Illinois department of Natural Resources. Journal of Fish and Wildlife Management, 2(1), 3–11. https://doi.org/10.3996/092010-JFWM-034

Swain, D. L., Wing, O. E. J., Bates, P. D., Done, J. M., Johnson, K. A., and Cameron, D. R. (2020). Increased Flood Exposure Due to Climate Change and Population Growth in the United States. Earth’s Future, 8(11). https://doi.org/10.1029/2020EF001778

Taft, O.W., Colwell, M.A., Isola, C.R., Safran, R.J. (2002). Waterbird responses to experimental drawdown: implications for the multispecies management of wetland mosaics. In Journal of Applied Ecology (Vol. 39).

Williams, C.K., Dugger, B., Brasher, M.G., Coluccy, J.M., Cramer, D.M., Eadie, J.M., Gray, M.J., Hagy, H. M., Livolsi, M., McWilliams, S.R., Petrie, M., Soulliere Gregory J., Tirpak, J.M., and Webb, E. B. (2014).

Estimating habitat carrying capacity for migrating and wintering waterfowl: Considerations, pitfalls and improvements. Wildfowl, Special Issue(4), 407–435.
https://www.researchgate.net/publication/269095790

Fig. 1 The abundance of dabbling ducks present in each basin over the wintering period

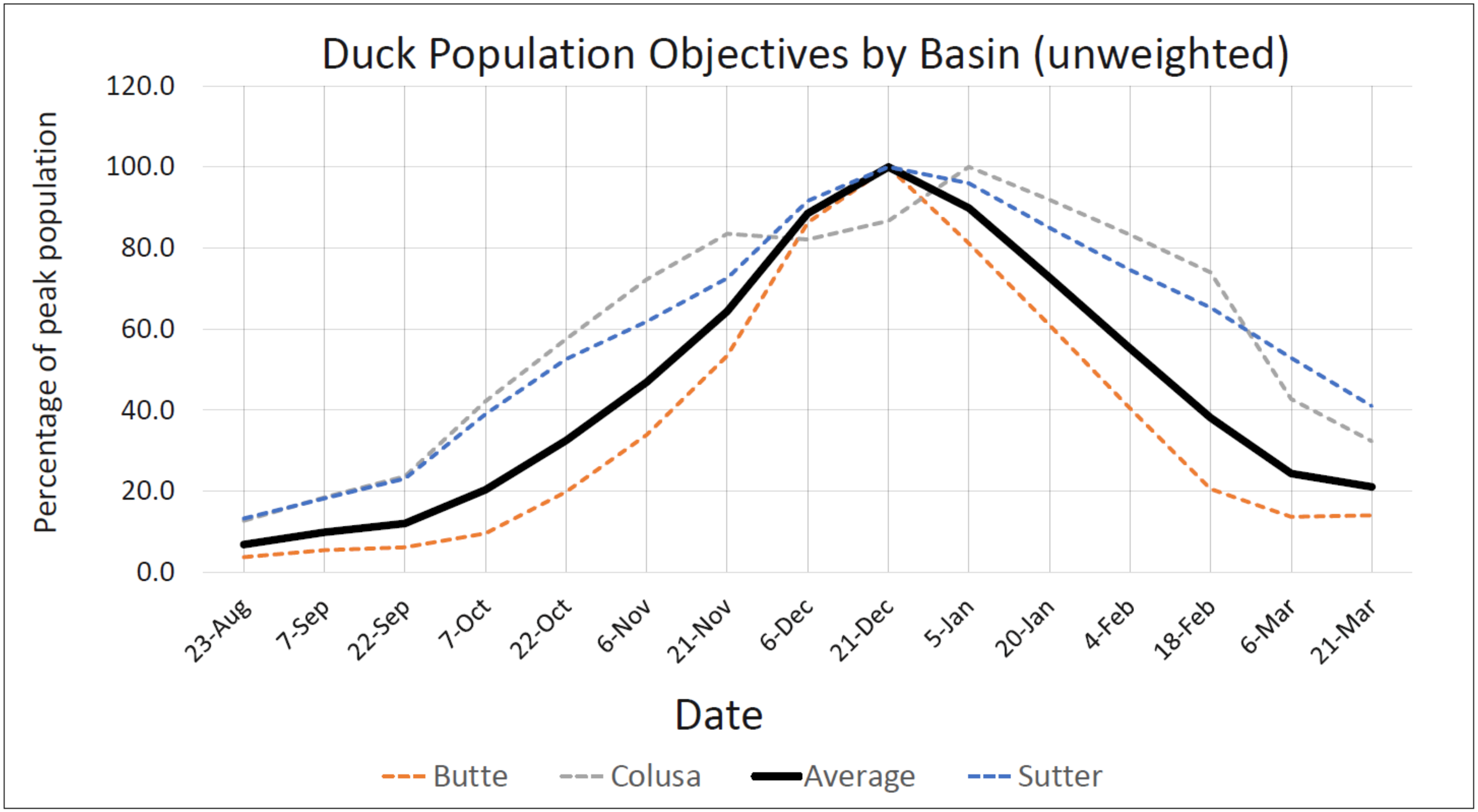

Fig. 2 The abundance of geese, by type, present in each basin over the wintering period

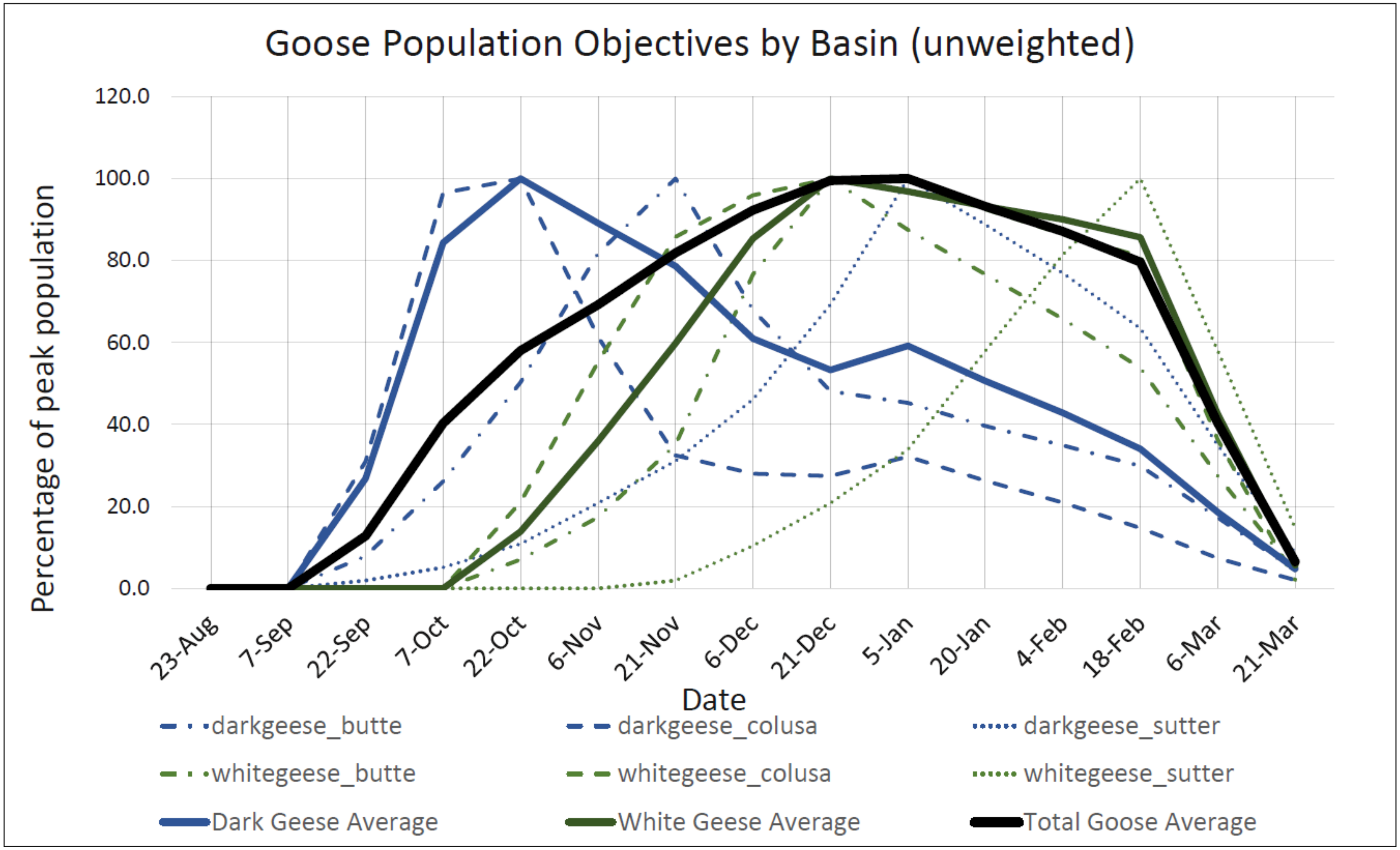

Fig. 3 The abundance of forager type over time within the project area

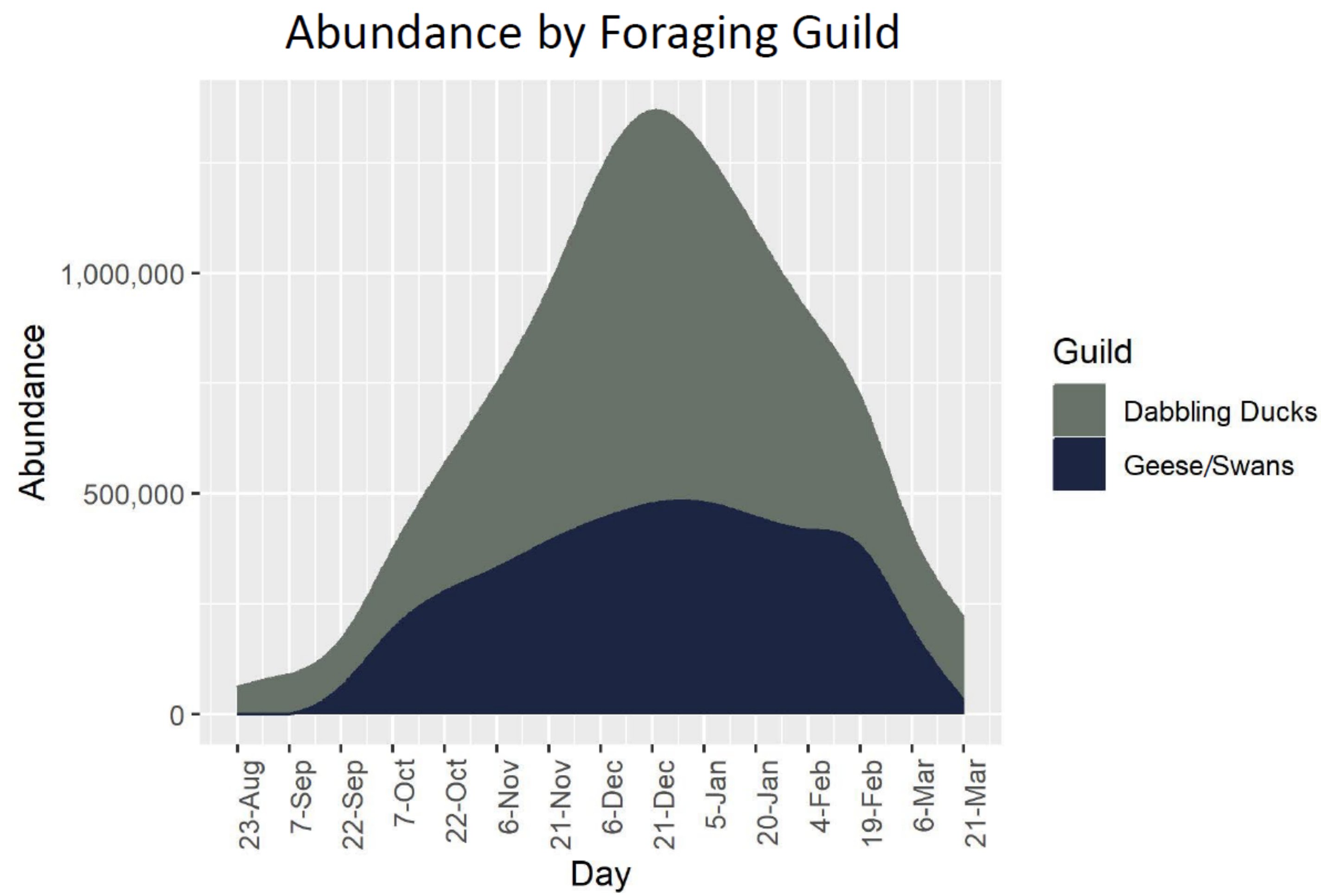

Fig. 4 The available area for waterfowl to forage in each habitat type over time, by water year.

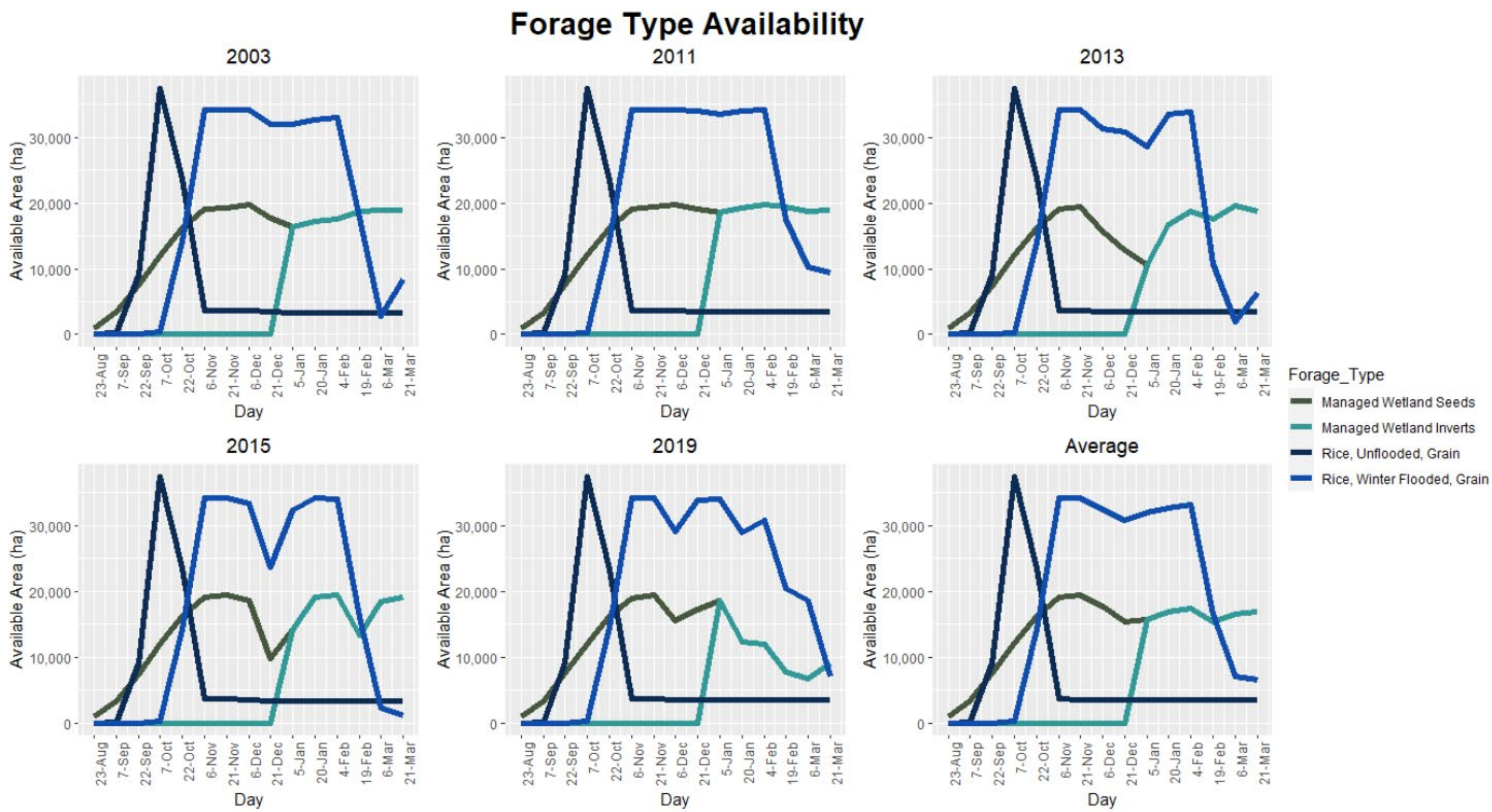

Fig. 5 The available energy for each food type over time, by water year.

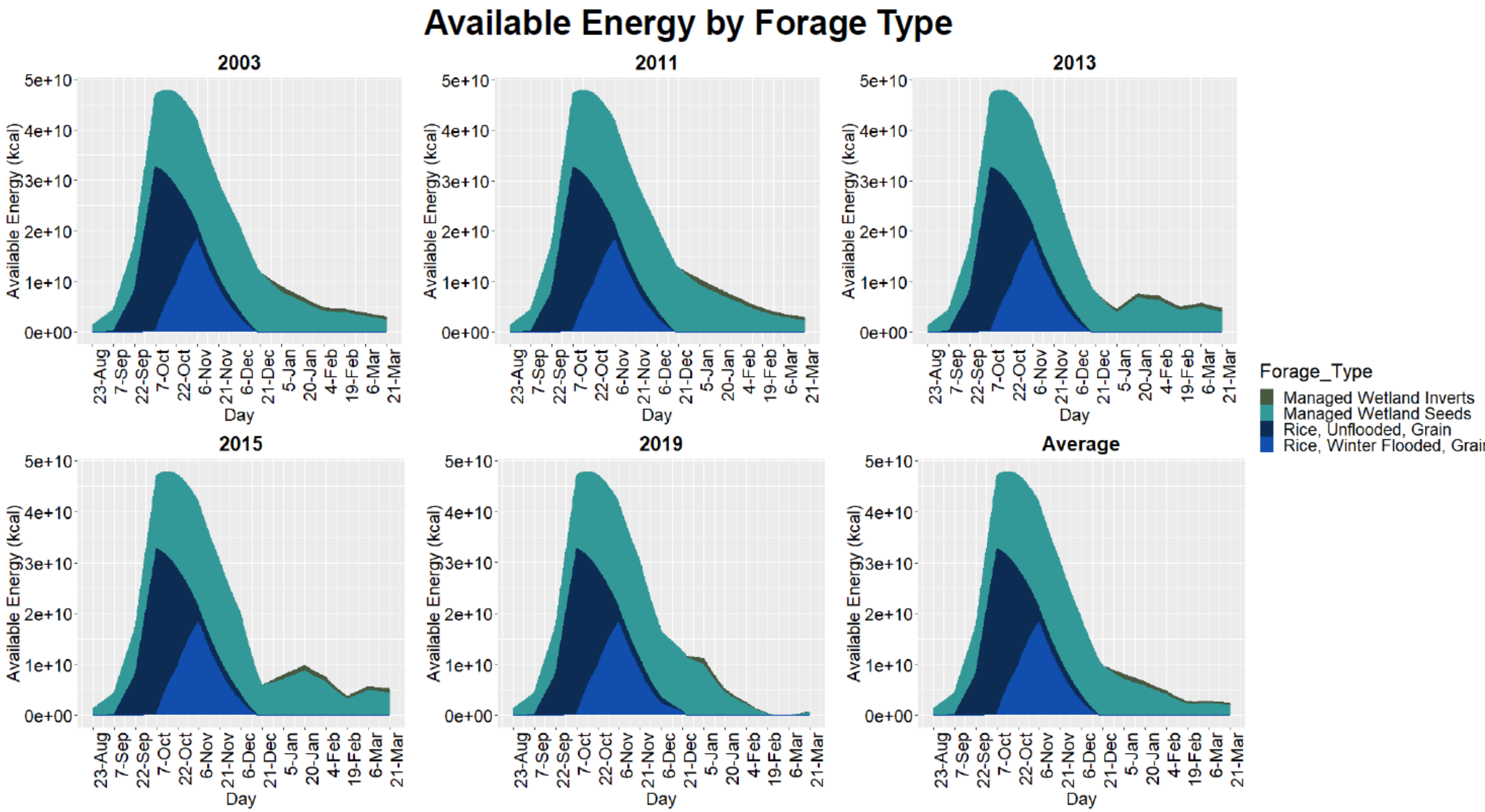

Fig. 6 The daily energy supply and demand curves for the project area by water-year