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EMERGENT INSECT PRODUCTION IN POST-HARVEST FLOODED AGRICULTURAL FIELDS USED BY WATERBIRDS

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Abstract: California's Tulare Lake Basin (TLB) is one of the most important waterbird areas in North America even though most wetlands there have been converted to cropland. To guide management programs promoting waterbird beneficial agriculture, which includes flooding fields between growing periods, we measured emergence rates of insects, an important waterbird food, in three crop types (tomato, wheat, alfalfa) in the TLB relative to water depth and days flooded during August–October, 2003 and 2004. We used corrected Akaike's Information Criterion values to compare a set of models that accounted for our repeated measured data. The best model included crop type and crop type interacting with days flooded and depth flooded. Emergence rates (mg m^{-2} day^{-1}) were greater in tomato than wheat or alfalfa fields, increased with days flooded in alfalfa and tomato but not wheat fields, and increased with water depth in alfalfa and wheat but not tomato fields. To investigate the relationship between the range of diel water temperatures and insect emergence rates, we reared *Chironomus dilutus* larvae in environmental chambers under high (15–32°C) and low fluctuation (20–26°C) temperature regimes that were associated with shallow and deep (respectively) sampling sites in our fields. Larval survival (4×) and biomass (2×) were greater in the low thermal fluctuation treatment suggesting that deeply flooded areas would support greater insect production.

Key Words: California, flooding depth, flooding duration, Tulare Lake Basin, waterbird food, waterfowl

INTRODUCTION

The Tulare Lake Basin (TLB), which included the historic Tulare Lake and its associated wetland complex, in California's southern San Joaquin Valley was once critical habitat for millions of migratory birds traveling the Pacific Flyway (Weis 1938). The Tulare Lake was originally11.7 m deep at its fullest, covered 198,296 ha, and was the nexus of a wetland complex that covered over 263,046 ha (Hansen 1994, Natureali.com 1998). However, like many other wetlands in California, expanding agriculture in the early 1900s created an increased demand for water and farmland, and eventually led to a reduction of Tulare Lake and its associated wetlands (Kirk 1994). As a result, the landscape in and around the Tulare Lake changed drastically, and what was once the largest freshwater body west of the Mississippi River (Jackson et al. 1990) has been converted into one of the most productive agricultural areas in the world.

Currently, parts of the TLB become periodically inundated during extreme flood events. However, only remnants of the historic wetland area in the TLB remain and are either confined primarily to privately owned waterfowl hunting clubs, former agricultural ground that has been enrolled in wetland reserve programs, and the Pixley and Kern National Wildlife Refuges. Because of altered hydrology and the high cost and low availability of water, most of these wetlands do not flood until late fall. Abundance of waterbirds in the Tulare Lake Basin declined along with habitat (Barnum and Euliss 1991, Kirk 1994, Fleskes et al. 2005).

Each year, some TLB fields are flooded after harvest to remove accumulated salts, control crop disease, and provide soil moisture. Post-harvest, late summer flooding, typically begins in mid-August and lasts through October (November in some years). Shortly after rotational crops are harvested during July and August, fields are filled with water up to 1 m deep. Head pressure from the water drives

the accumulated salts into underground tile drains and out of the fields. Inundation of soils for as long as six weeks during ambient temperatures of ≥ 30°C is an effective means of fungal control (Rourke and Nehl 2001). Despite these multiple benefits, the cost and availability of water for flooding fields after harvest influences the amount of flooding in the TLB.

Of the limited wetland habitat available, flooded agricultural fields are the most common wetland habitat in the TLB during August–October (Fleskes 1999) and they support large populations of waterbirds during this time of year. About 20–50% of shorebirds counted in the TLB during 1992–95 (Shuford et al. 1998) and 59–74% of the waterfowl counted in the TLB during 1980–87 (Barnum and Euliss 1991) were on post-harvest flooded agricultural fields. Fleskes et al. (2003) reported that northern pintails (*Anas acuta*), the most abundant waterfowl species wintering in the TLB (Barnum and Euliss 1991), selected flooded fallow and post-harvest flooded safflower fields and avoided post-harvest flooded alfalfa and cotton fields. Their use of post-harvest flooded wheat/barley fields varied greatly.

Factors affecting differential use of TLB fields by waterbirds have not been previously investigated. Most waterbirds are opportunistic and select feeding habitats that provide abundant food (Bellrose 1980, Austin and Miller 1995). The most common waterbirds wintering in the TLB (i.e., dabbling ducks and shorebirds) prefer to forage in flooded habitats that are shallow (e.g., ≤ 30 cm) enough for them to access invertebrates and other foods in the substrate (Safran et al. 1997, Isola et al. 2000). Managed flooded areas are vital as resting areas for migratory and nesting waterbirds as well as an energy source through foraging on plants and invertebrates. Invertebrates in particular are critical sources of energy and protein (Taft and Haig 2005) for both resident and migratory waterbirds (Beam and Gruenhagen 1980, Connelly and Chesemore 1980, Euliss 1984, Miller 1987). Ducks feeding in marshes and evaporation ponds in TLB rely heavily upon larval Chironomidae (Diptera) throughout the winter (Euliss and Harris 1987, Euliss et al. 1991). For example, chironomids (mostly adults and pupae) comprised as much as 85% of the diet volumes of pintail ducks feeding in the Los Banos Wildlife Area (Connelly and Chesemore 1980). Flooding wetlands during late summer rather than in fall as is the current practice (Fleskes et al. 2003), provided additional benefit for waterbirds by creating habitat types that were favorable for opportunistic chironomids that are a known prey species of dabbling ducks (Batzer et al. 1993, Batzer et al. 1997). Thus, variation in the availability of chironomids and other aquatic invertebrates between crop types may determine the value and use of TLB fields by waterbirds (Fleskes et al. 2003).

Currently no information is available on the densities or production of waterbird insect prey in TLB fields or how they vary among crop types or other factors such as flooding depth and duration. Having such information would assist the Central Valley Joint Venture (Central Valley Habitat Joint Venture Implementation Board 1990) and other waterbird conservation programs in determining habitat values and estimating the potential waterbird food base in flooded agricultural fields. The goals of this study were to evaluate variation in insect emergence as an index of insect production among three crop types and flooding depths, flooding durations, and temperature regimes, and thus assess the relative habitat values of flooded agricultural fields for waterbirds.

STUDY AREA

We studied invertebrates in flooded fields within the TLB (Figure 1). The TLB is generally defined as land at or below the 63 m elevation line, at approximately latitude 36°00′N., longitude 119°45′W (Tulare Lake Basin Water Storage District 1981). We obtained access permission from two landowners in the TLB and from the Bureau of Land Management. We selected fields opportunistically, according to what fields were scheduled for flooding by the landowners. Crop types that were analyzed were similarly dependent upon pre-existing landowner schedules. Only fields that were planned to be flooded for a minimum of 20 days during August to October were selected; actual duration of flooding ranged from 21–48 days. The field portion of this study was conducted on two flooded alfalfa fields in 2003 and four flooded wheat and five flooded tomato fields in 2004. Fields varied from 5 to 190 ha each, and totaled approximately 668 ha.

METHODS

Insect Emergence

We measured rates of insect emergence from flooded wheat, tomato, and alfalfa fields using modified emergence traps (LeSage and Harrison 1979). We constructed traps using a 0.25 m^2 square base of ABS plastic pipe, with four 1 cm wooden dowels inserted into the corners. For each trap, the dowels supported a Plexiglas collecting head, kill jar

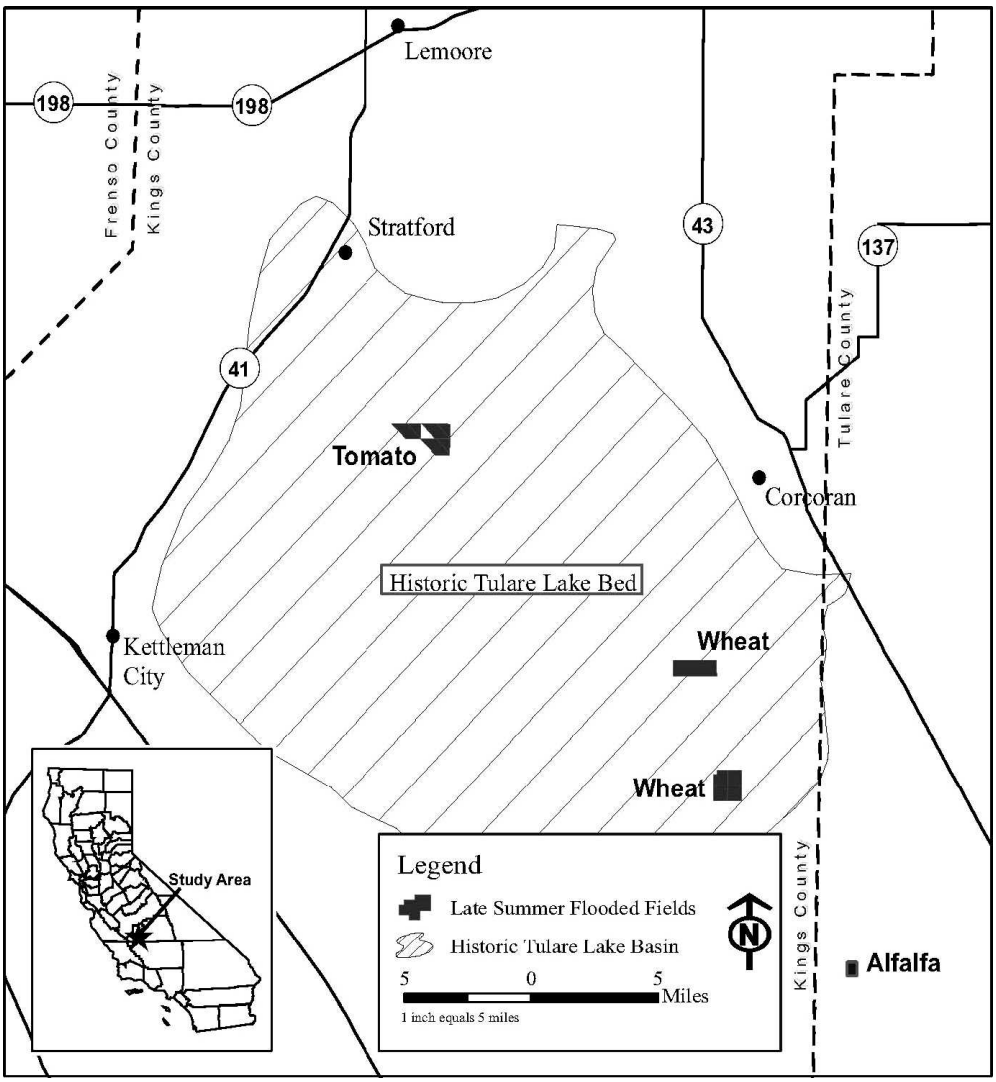

Figure 1. Map of Tulare Lake wetland complex in central California showing locations of study areas by crop type.

and netting, and connected the collecting head to the base. We constructed each kill jar using a 500 ml polypropylene jar with a foam-lined lid in which we cut a hole to match the exit hole into the Plexiglas collecting head. Each jar was filled with approximately 250 ml of killing solution, made by combining equal parts ethylene glycol, ethanol, and water (F. Schreiber, California State University-Fresno, personal communication). We floated the traps on the surface of the water and anchored them to the substrate with a 30 cm reinforcing bar or wooden dowel. The weight of each trap forced 1–2 cm of the base below the surface of the water, effectively preventing the traps from collecting neustonic insects. In 2003, we attached HOBO StowAway Tidbit temperature loggers (Onset Computer Corporation) underwater on the substrate beneath each trap. The loggers collected water temperature every 30 seconds. We attached temperature loggers to the traps in 2004, but all were lost in the fields after a large rainstorm.

We installed emergence traps at least 10 days after each field was completely flooded. This interval was to allow aerially dispersing insects adequate time to lay eggs, complete larval development, and emerge as adults (Oliver 1971, Gray 1981, Euliss 1984, Pritchard et al. 1996). This delay also avoided variability in production associated with differences in abundance of aquatic insect eggs and larvae existing in water pumped into the fields and allowed us to focus on measuring the impacts of field characteristics (e.g., crop type, water depth) on production. We deployed three traps in each field using a stratified random design to account for potential within-field variation in flooding depth. Agricultural fields in the TLB have been engineered with a slope to facilitate the movement of water across the field for both flooding

Table 1. Models of $\log_{10}$-transformed emergence rate (mg m^{-2} day^{-1}) ranked from most to least supported based on Akaike's Information Criterion (AIC_c) (k = number of parameters, CT = Crop Type, DeF = Depth of Flooding, DaF = Days Flooded).

Model terms	k	−2 log likelihood	AICc	ΔAICc	AICc wt
CT+DaF+DeF+CT*DeF+CT*DaF	11	46.4	70.3	0.0	0.387
CT+DaF+DeF+CT*DaF	9	51.6	70.8	0.6	0.294
CT+DaF+DeF+CT*DaF+DeF*DaF	10	50.9	72.4	2.1	0.132
CT+DaF+DeF+CT*DeF+DeF*DaF+CT*DaF	12	46.4	72.6	2.3	0.120
CT+DaF+CT*DaF	8	57.3	74.3	4.0	0.052
CT+DeF+DaF+DeF*DaF+CT*DaF+CT*DeF+CT*DaF*DeF	14	45.9	77.0	6.7	0.014
CT+DaF+DeF+CT*DeF+DeF*DaF	10	67.5	89.1	18.8	0.000
CT+DaF+DeF+CT*DeF	9	72.4	91.6	21.4	0.000
CT+DeF+DaF	7	77.4	92.2	21.9	0.000
CT+DaF+DeF+DeF*DaF	8	75.3	92.3	22.0	0.000
CT+DaF	6	81.5	94.1	23.8	0.000
CT+DeF+CT*DeF	8	85.6	102.6	32.4	0.000
CT+DeF	6	90.8	103.4	33.2	0.000
CT	5	94.1	104.5	34.3	0.000
DeF+DaF+DeF*DaF	6	101.2	113.8	43.5	0.000
DeF+DaF	5	103.9	114.3	44.1	0.000
DeF	4	109.6	117.9	47.6	0.000
DaF	4	110.2	118.5	48.2	0.000
Null	3	120.9	127.1	56.8	0.000

and draining. To control for possible within-field variation due to that slope, we partitioned the fields into three depth gradient sections and randomly placed traps within each section. We measured water depth at each trap when the trap was set. We collected trap contents every 3–4 days and installed new kill jars with fresh killing solution. Water level likely varied little across collection periods since land owners replenished water lost to evaporation, but were unlikely to add excess water due to cost and height of the earthen border.

We separated the insects from the remaining preservative solution and stored them in labeled jars with 70% ethanol. We sorted insects collected from each trap/day by taxonomic family using keys in Merritt and Cummins (1996). To expedite analysis of large captures, we sub-sampled collected individuals by placing all collected individuals from a single trap and collecting interval into a square dish with a grid of 13 × 13 mm squares. We then identified and counted the individuals within five randomly selected squares. Mass was determined by taking representative samples of each family, oven drying the samples at 80°C for 48 hours (to constant mass), and then determining the average per capita weight per family to the nearest 0.01 g. The average weights from each family were then multiplied by the number of individuals from each family to obtain a total biomass for that taxa in each sample.

We measured three field characteristics, crop type (CT), depth of flooding (DeF), and days flooded (DaF), which each were of interest to management, and systematically investigated their relationship to insect emergence rates. Each emergence trap sample represented an experimental unit and was quantified as both the number and biomass of emerged insects per m^2 per day. However, since habitat programs require estimates of waterbird prey biomass production, we focused most analysis on biomass rather than the number of individuals that emerged. Emergence rates were log-transformed prior to model analysis to reduce the influence of extreme values.

To best account for correlated data due to repeated measurements in our sample design, we first investigated five data correlation structures in a global model containing all CT, DeF, and DaF effects and interactions: [i] random field effects, where trap samples from the same field vary less than samples among different fields; [ii] combination random field and trap effects, where samples from the same trap vary less than samples from different traps; [iii] a first-order autoregressive structure (AR[1]), in which consecutive samples from the same trap are more correlated than samples separated farther in time; [iv] combination of [i] and [iii]; and [v] complete independence among samples (Littell et al. 1996). After selecting the best data correlation structure, we compared models based on various combinations of CT, DeF, and DaF including models with 2- and 3-way interactions (Table 1). We analyzed these models using the SAS (SAS Institute 2004) PROC MIXED proce-

dure. We determined the best correlation structure and best combination of field characteristics by finding the models with the lowest Akaike's Information Criterion term (AICc) and greatest AIC_c weights (Burnham and Anderson 2002).

We calculated invertebrate production in flooded fields by applying Emergence-to-Production (mg m^{-2} day^{-1}) (E:P) ratios (Jackson and Fisher 1986) to our estimates of emergence. We used emergence traps instead of repeatedly collecting soil core samples to measure invertebrate production (Waters 1977, Benke 1984). Previous soil core sampling in similar habitats by other researchers found a high frequency of cores with no larvae and extreme difficulty in traversing the unconsolidated field bottoms to collect cores (D. Barnum, personal communication). Emergence traps also afforded greater sampling area compared to cores. The calculation of production from emergence data assumes that the factors controlling production (e.g., faunal composition, temperature, food resources, birth and death rates) in our and Jackson and Fisher's (1986) environments were similar. Jackson and Fisher's (1986) environment, while a stream, was similar to flooded fields in having very low discharge, and similar mean temperatures during the equivalent time period. Neither habitat was suspected to be limited by nutrients. Because abiotic conditions and emergence rates in Jackson and Fisher's system during their periods I and III were most similar to our flooded fields, we used the average daily E:P ratio of those two periods (0.252) to calculate chironomid production in each of our field types based upon our emergence data. Emergence rates of chironomids in both systems were nearly identical and E:P ratios were derived from similar taxa.

Temperature Effects on *Chironomus* Survival and Biomass

Early in the first year of the field study we noticed a negative relationship between water depth and range of daily water temperatures and a positive relationship between insect emergence rate and water depth. To investigate these relationships, we developed a controlled growth chamber experiment to measure effects of water temperature fluctuation on chironomid survival and growth. We programmed two Conviron E15 environmental chambers to mimic temperature fluctuation regimes that we measured in shallow (ca. 15 cm) and deeply flooded (ca. 90 cm) field sections. We corrected for the difference between air temperature fluctuation programmed into the environmental chambers and the measured water temperature fluctuation by placing temperature loggers in the same conditions (water volume, container, etc.) planned for the larval survival and biomass trials. We then adjusted air temperatures to create the intended diel water temperature fluctuations. We programmed the first chamber to have a 17°C daily water temperature amplitude (i.e., high fluctuation chamber) fluctuating between 15°C and 32°C, as observed in shallow water, and the second chamber to have 6°C daily (i.e., low fluctuation chamber) water temperature amplitude fluctuating between 21°C and 27°C, as observed in deep water.

We used *Chironomus dilutus* egg masses from the United States Geological Survey (USGS) laboratory culture in Columbia, Missouri, because they are a commonly cultured and available test species. Also, relatively large *Chironomus* midges such as this species are important waterbird food (Batzer et al. 1993). We divided the egg masses into groups of approximately 20 eggs each and randomly placed groups into fourteen 500 ml polyethylene jars containing 2 cm of fine washed sand and 80 ml of conditioned tap water (2 cm depth). We continued to randomly allocate egg mass groups to each jar until each held approximately 200 eggs. The 14 jars were then randomly assigned to one of the two treatment regimes (7 jars per each treatment) and immediately placed into the appropriate environmental chamber. We then provided the jars with light aeration and covered them with netting (0.7 mm mesh size). Two days after the eggs hatched, the chironomid larvae were fed 0.04 g of Tetramin Flakes (Tetra Werke Company) blended with conditioned water (E. Greer, USGS, Columbia Environmental Research Center, personal communication). We supplied food every three days and maintained water in each jar at 80 ml volume by adding conditioned water daily as necessary. We changed water weekly by pipetting surface water out and re-filling the jars with clean, conditioned water. Larvae grew in the environmental chambers for 30 days. The constant depth across both temperature flux regimes allowed us to directly address the effects of temperature fluctuation alone while controlling for other potential effects of water depth. After 30 days, we poured the entire jar contents through a 255 μm sieve. We counted living larvae (all were live) and preserved them in vials containing 70% ethanol. We estimated total larval biomass from each replicate to the nearest 0.01 g by weighing all larvae from a vial together after drying them at 80°C for 48 hours (to a constant dry weight [DW]) in aluminum weigh boats. We compared the numbers and total biomass of surviving larvae grown under the two temperature regimes with Student t-tests for independent samples.

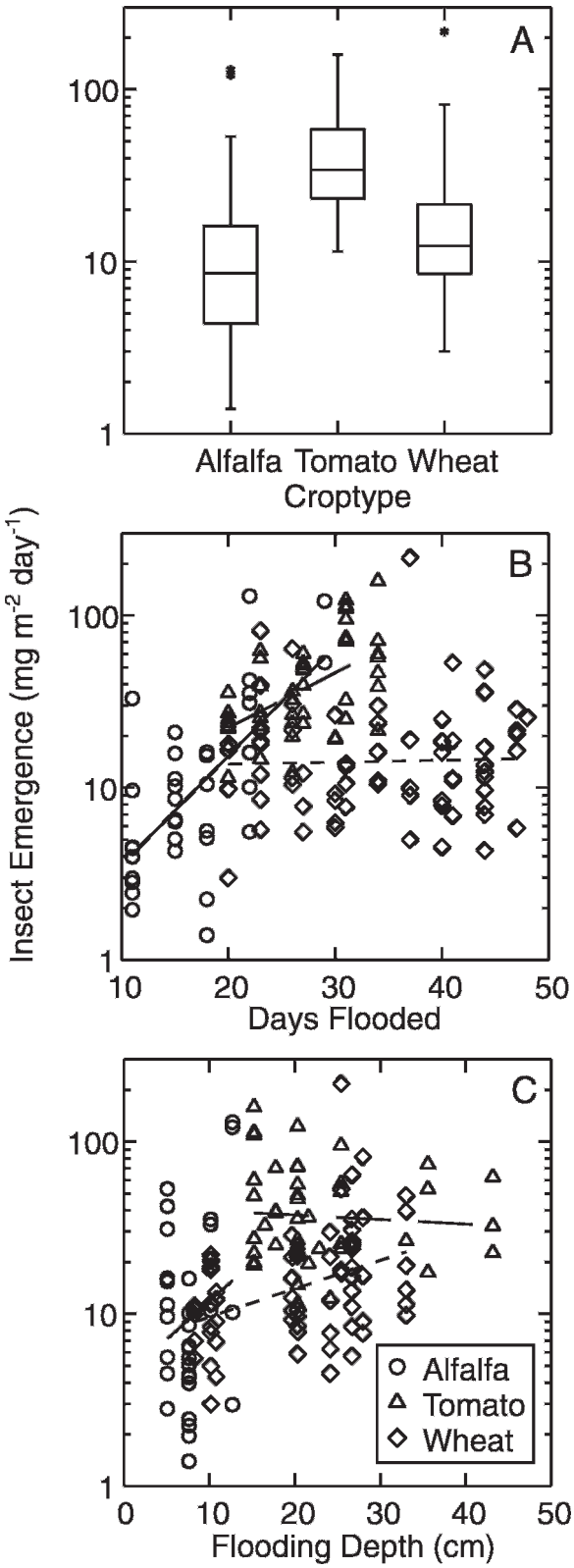

Figure 2. Rate of insect emergence (mg m^{-2} day^{-1}) during each of five, 3–4 day sampling intervals on post-harvest flooded fields during August–October, 2003 and 2004 by A) crop type , B) duration of field flooding, and C) depth of field flooding at emergence trap location. In A, the center horizontal lines in box and whisker plots are the median value, upper and lower horizontal box lines are 75th and 25th percentiles respectively, while whisker ends represent 10th and 90th percentiles of the data. In B and C, lines are based on least squared regression for each crop type.

RESULTS

Field Insect Emergence

We collected over 56,000 emerged insects (mostly Chironomidae) from three different crop types (tomato, wheat, alfalfa) during 609 days of trapping from 6 September to 29 October 2003 and 21 August to 18 October 2004. Duration of flooding at the time we collected samples ranged from 11–48 days, and depth of water below traps ranged from 5–43 cm. Log_{10}-transformed rates (m^{-2} day^{-1}) of emerged individuals and their total biomass was highly correlated ($r = 0.772$, $n = 152$, $P < 0.001$; biomass = 0.836(# individuals) − 0.202; $SE_{slope} = 0.037$), likely due to low taxonomic diversity at the Family level within and across treatments. We fit models that contained correlations between consecutive measurements from repeatedly sampled traps because there was substantial evidence in the data for this correlation (first-order autoregressive structure: AIC_c weight = 69.1%) compared to no correlation (independence structure: 8.3%) or any of the remaining forms of correlations associated with random trap or field effects (combined AIC_c weight = 22.6%). Models with all three variables (CT, DaF, DeF) best represented emerged mass (combined AIC_c weight 94.8%; Table 1), although they represented only 9 of the 19 models examined. Models including CT*DaF interaction had the highest combined weight (100%) compared to the other interaction terms, CT*DeF (52.1%) or DeF*DaF (26.6%).

Average emerged mass was greater in tomato fields (181 mg m^{-2} day^{-1}, SE = 18, range = 46–636) than either wheat fields (81.3 mg m^{-2} day^{-1}, SE = 13, range = 12–868) or alfalfa fields (75 mg m^{-2} day^{-1}, SE = 20, range = 6–520) (Figure 2a). The best model contained CT*DaF and CT*DeF interactions, indicating differences among crop types in the relationship between emergence rate and the days and depth of flooding (alfalfa: log_{10} mg emerged m^{-2} day^{-1} = −0.2958 + 0.0616DaF + 0.0329DeF; tomato: log_{10} mg emerged m^{-2} day^{-1} = 0.7605 + 0.0300DaF − 0.0003DeF; wheat: log_{10} mg emerged m^{-2} day^{-1} = 0.7073 + 0.0031DaF + 0.0166DeF). Insect emergence increased with days flooded in alfalfa and tomato

but not wheat fields (Figure 2b) and increased with water depth in alfalfa and wheat but not tomato fields (Figure 2c).

Taxonomic Composition. Chironomidae was the most common family of insects that emerged from all field types (tomato: 96.2%; wheat: 90.4%; alfalfa: 56.8%). Muscidae (Diptera) was the second most common family, with alfalfa fields supporting the highest proportion (tomato: 2.8%; wheat: 6.8%; alfalfa: 38.9%). Other insects which averaged > 0.2% of trap contents across fields included Heleomyidae, Hymenoptera, Coleoptera, and Culicidae.

Daily Chironomid Production. Emerged dry mass of chironomids in tomato, wheat, and alfalfa fields averaged 145.9, 46.8, and 29.2 mg m^{-2} day, respectively. Daily production (calculated by dividing the emerged dry mass by the 0.252 E:P ratio) for tomato, wheat, and alfalfa fields was 578.8, 185.8, and 115.7 mg m^{-2} day, respectively.

Temperature Effects on *Chironomus* Survival and Biomass

The number of live chironomid larvae that survived differed between the low fluctuation ($\bar{x}$ = 33.6 individuals, SE = 4.7, range = 15–48) and high fluctuation ($\bar{x}$ = 8.9 individuals, SE = 2.6, range = 0–17) treatments (t_{12} = 4.6, P = 0.0006). Total biomass of chironomid larvae also differed between the low fluctuation treatment ($\bar{x}$ = 39.60 mg DW, SE = 3.74, range = 24.9–54.3) and high fluctuation treatment ($\bar{x}$ = 19.64 mg DW, SE = 5.57, range = 0–35.4) (t_{12} = 2.98, P = 0.012). However, the mean mass of individual larvae in the high fluctuation treatment ($\bar{x}$ = 2.36 mg DW/larvae) was nearly 2× that in the low fluctuation treatment ($\bar{x}$ = 1.28 mg DW/larvae)(t_{12} = 4.11, P = 0.0017).

DISCUSSION

Our results indicate that differential use of flooded fields by northern pintails and other waterbirds reported by Fleskes et al. (2003) may be at least partially due to differences in aquatic insect emergence among crop types. We found that a combination of crop type, flooding duration, and flooding depth best explained variation in emerged insect mass. Tomato fields had a higher average emerged mass than either alfalfa or wheat fields. We suspect that these differences may be due to differences in the amount of residual crop biomass left after harvest. Alfalfa and wheat harvest leaves relatively little above ground plant biomass in the fields whereas the bulk of the tomato plant is left in the field after fruit are pulled from the vines (R. Moss, personal observation). This additional plant biomass could enhance insect production in two ways. First, the decaying organic matter could directly provide a food resource for detritivorous aquatic insects, and indirectly through the enhanced availability of inorganic nutrients available for autochthonous primary production (Batzer and Resh 1992). Secondly, the additional plant biomass in tomato fields could enhance habitat complexity (e.g., additional structure, microhabitat) resulting in higher insect densities relative to other crop types.

We did not measure emergence production until after fields had been inundated for at least 10 days. The time required for chironomids to establish populations is extremely unpredictable because eggs and larvae may be present in some water sources but not others (Euliss and Grodhaus 1987). Adult chironomids can develop from eggs in as little as nine days in warm environments (Gray 1981, Hauer and Benke 1991). Thus, the 10 day flooding-trapping interval increased the likelihood that the emerging adults we trapped had developed from eggs laid by aerially dispersing adults rather than from eggs or larvae present in flood waters, and reduced variability in production that could have been caused by differences in water sources, allowing us to focus on measuring impacts of field characteristics (e.g., crop type, water depth) on production. Until further information becomes available, we speculate that chironomid production was zero when water was first applied, and then increased until day 10 to reach the crop-type averages we report.

Observed relationships between water depth, emerged biomass, insect productivity, and survival is consistent with other chironomid research (see de Szalay et al. 1999) and help explain the considerable spatial heterogeneity in insect emergence and emerged mass within each field as was indicated by the high autocorrelation of samples. Depth and its effect on the benthic habitat temperature fluctuations in this system appear to play an important role in the survival and growth of chironomids. Maintaining a water depth of 1 m (the deepest we measured except for the borrow ditch ringing each field) in fields would reduce temperature fluctuation and should produce more invertebrates than more shallow water. However, the water costs to maintain deeply flooded fields could be prohibitive and would probably reduce flooded field acreage. Also, most waterbird species that use these fields (e.g., shorebirds and dabbling ducks) optimally forage in water ≤ 30 cm deep (Safran et al. 1997, Isola et al. 2000). Providing a range of fields depths through grading,

discing, timing of flooding, or other management techniques could promote both aquatic insect production and optimal waterbird foraging. Thus, we recommend that most of the field be maintained at ≤30 cm but with some areas of deeper water which would provide neustonic chironomid pupae and pre-flight adults for surface-feeding waterbirds (Batzer and Resh 1992, Batzer et al. 1993, Batzer et al. 1997).

Our results also indicated that increased flooding duration increased emerged mass. This seems to be consistent with an increasing level of colonization following the flooding of the fields (Batzer et al. 1997). It is difficult to make specific flooding duration recommendations because we were not able to observe the fields longer than the agricultural practices permitted and thus were not able to note changes as colonization may have reached carrying capacity. Habitat value for water birds is only present when fields are flooded, thus we recommend flooding for the maximum duration practicable, while still meeting agricultural requirements.

Practices that improve the wildlife value of agricultural fields in the TLB would greatly improve local habitat conditions for waterbirds and other wildlife. Nearly all of the TLB is currently managed as highly valuable and productive agricultural ground. Although large areas of the TLB sometimes flood in late winter, the scarcity of late summer habitat is likely an important factor limiting regional waterbird abundance (Fleskes et al. 2002). Most efforts to aid wildlife recovery in the region have focused on taking marginal agricultural ground out of production and restoring it to wetlands. While vital for maintaining wildlife populations, this effort has occurred at a relatively small scale and is not likely to create enough suitable habitat to fully restore waterbird populations in the region. Cooperative management programs, such as the Landowner Incentive Program, which is an effort to reverse the decline of special status species in the Central Valley of California through enhancement and management of private lands (Landowner Incentive Program 2005), could greatly enhance the waterbird value of these agricultural fields by suggesting appropriate crop type, flooding depth and duration, while maintaining or even improving agricultural production.

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LITERATURE CITED

Austin, J. E. and M. R. Miller. 1995. Northern Pintail (*Anas acuta*). p. 1–32. *In* A. Poole and F. Gill (eds.) The Birds of North America, No. 163. The Academy of Natural Sciences, Philadelphia and The American Ornithologists Union, Washington, DC, USA.

Barnum, D. A. and N. H. Euliss, Jr. 1991. Impacts of changing irrigation practices on waterfowl habitat use in southern San Joaquin Valley, California. California Fish and Game 77:11–22.

Batzer, D. P. and V. H. Resh. 1992. Macroinvertebrates of a California seasonal wetland and responses to experimental habitat manipulation. Wetlands 12:1–7.

Batzer, D. P., F. A. de Szalay, and V. H. Resh. 1997. Opportunistic response of a benthic midge (Diptera: Chironomidae) to management of California seasonal wetlands. Environmental Entomology 26:215–22.

Batzer, D. P., M. McGee, V. H. Resh, and R. R. Smity. 1993. Characteristics of invertebrates consumed by mallards and prey response to wetland flooding schedules. Wetlands 13:41–49.

Beam, J. and N. Gruenhagen. 1980. Feeding ecology of pintails (*Anas acuta*) wintering on the Los Banos Wildlife Area, Merced County, California. California Department of Fish and Game, Federal Aid Wildllife Restoration Progress Report, Project W–40-D–1.

Bellrose, F. C. 1980. Ducks, Geese, and Swans of North America. Stackpole Books, Harrisburg, PA, USA.

Benke, A. C. 1984. Secondary production of aquatic insects. p. 289–322. *In* V. H. Resh and D. M. Rosenberg (eds.) The Ecology of Aquatic Insects. Praeger Publishers, New York, NY, USA.

Burnham, K. P. and D. R. Anderson. 2002. Model Selection and Multimodel Inference: A Practical-Theoretic Approach, 2nd ed. Springer-Verlag, New York, NY.

Central Valley Habitat Joint Venture Implementation Board. 1990. Central Valley Habitat Joint Venture Implementation Plan. North American Waterfowl Management Plan, Portland, OR, USA.

Connelly, D. P. and D. L. Chesemore. 1980. Food habits of pintails (*Anas acuta*), wintering on seasonally flooded wetlands in the northern San Joaquin Valley, California. California Fish and Game 66:233–37.

de Szalay, F. A., N. H. Euliss, and D. P. Batzer. 1999. Seasonal and semipermanent wetlands of California; invertebrate community ecology and response to management methods.

p. 829–55. *In* D. P. Batzer, R. B. Rader, and S. A. Wissinger (eds.) Invertebrates in Freshwater Wetlands of North America: Ecology and Management. John Wiley and Sons, New York, NY, USA.

Euliss, N. H., Jr. 1984. The feeding ecology of pintail and green-winged teal wintering on Kern National Wildlife Refuge. Masters Thesis. Humboldt State University, Arcata, CA, USA.

Euliss, N. H., Jr. and G. Grodhaus. 1987. Management of midges and other invertebrates for waterfowl wintering in California. California Fish and Game 73:238–43.

Euliss, N. H., Jr. and S. W. Harris. 1987. Feeding ecology of northern pintails and green-winged teal wintering in California. Journal of Wildlife Management 51:724–32.

Euliss, N. H., Jr. R. L. Jarvis, and D. S. Gilmer. 1991. Feeding ecology of wintering waterfowl on evaporation ponds in California. Condor 93:582–90.

Fleskes, J. P. 1999. Ecology of female northern pintails during winter in the San Joaquin Valley, California. Ph.D. Dissertation. Oregon State University, Corvallis, OR, USA.

Fleskes, J. P., R. L. Jarvis, and D. S. Gilmer. 2002. Distribution and movements of female northern pintails radio-tagged in the San Joaquin Valley, California. Journal of Wildlife Management 66:138–52.

Fleskes, J. P., R. L. Jarvis, and D. S. Gilmer. 2003. Selection of flooded agricultural fields and other landscapes by female northern pintails wintering in Tulare Basin, California. Wildlife Society Bulletin 31:793–803.

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. United States Geological Survey – Western Ecological Research Center, Dixon Field Station, Dixon, California.

Gray, L. J. 1981. Species Composition and Life Histories of Aquatic Insects in a Lowland Sonoran Desert Stream. The American Midland Naturalist 106:229–42.

Hansen, R. B. 1994. A Fish Story Called Tulare Lake. California Heartland. College of the Sequoias, Visalia, CA, USA.

Hauer, F. R. and A. C. Benke. 1991. Rapid growth of snag-dwelling chironomids in a blackwater river: the influence of temperature and discharge. Journal of the North American Benthological Society 10(2):154–64.

Isola, C. R., M. A. Colwell, O. W. Taft, and R. J. Safran. 2000. Interspecific differences in habitat use of shorebirds and waterfowl foraging in managed wetlands of California's San Joaquin Valley. Waterbirds 23:196–203.

Jackson, J. K. and S. G. Fisher. 1986. Secondary production, emergence, and export of aquatic insects of a Sonoran Desert stream. Ecology 67:629–38.

Jackson, W. T., R. F. Herbert, and S. R. Wee. 1990. Engineers and Irrigation: Report of the Board of Commissioners on the Irrigation of the San Joaquin, Tulare and Sacramento Valleys of the State of California, 1873. Engineering Pamphlet 870-1-39, Office of History U. S. Army Corps of Engineers, Alexandria, VA.

Kirk, L. 1994. Vanished lake, vanished landscape. p. 171–79. *In* C. G. Thelander (ed.) Life On the Edge-A Guide to California's Endangered Natural Resources: Wildlife. Biosystems Books, Santa Cruz, CA, USA.

Landowner Incentive Program. 2005. California Landowner Incentive Program. http://www.dfg.ca.gov/lands/lip/lipinfo.pdf

LeSage, L. and A. D. Harrison. 1979. Improved traps and techniques for the study of emerging aquatic insects. Entomological News 90:65–78.

Littell, R. C., G. A. Milliken, W. W. Stroup, and R. D. Wolfinger. 1996. SAS System for Mixed Models. SAS Institute Inc., Cary, NC, USA.

Merritt, R. W. and K. W. Cummins. 1996. An Introduction to the Aquatic Insects of North America, third edition. Kendall/Hunt Publishing Co., Dubuque, IA, USA.

Miller, M. R. 1987. Fall and winter foods of northern pintails in the Sacramento Valley, California. Journal of Wildlife Management 51:403–12.

Natureali.com. 1998. http://www.natureali.org/KNWRvisitors.htm

Oliver, D. R. 1971. Life history of the Chironomidae. Annual Review of Entomology 16:211–30.

Prichard, G., L. D. Harder, and R. A. Mutch. 1996. Development of aquatic insect eggs in relation to temperature and strategies for dealing with different thermal environments. Biological Journal of the Linnean Society 58:221–44.

Rourke, K. and D. Nehl. 2001. Black Root Rot Update. Cotton Information Sheet. Australian Cotton Cooperative Research Centre, Narrabri, NSW, Australia.

Safran, R. J., C. R. Isola, O. E. Williams, and M. A. Colwell. 1997. Benthic invertebrates at foraging locations of ten waterbird species in managed wetlands of the northern San Joaquin Valley, California. Wetlands 17:407–15.

SAS Institute. 2004. SAS OnlineDoc 9.1.2. SAS Institute Inc., Cary, NC, USA.

Shuford, W. D., G. W. Page, and J. E. Kjelmyr. 1998. Patterns and dynamics of shorebird use of California's Central Valley. Condor 100:227–44.

Taft, O. W. and S. M. Haig. 2005. The value of agricultural wetlands as invertebrate resources for wintering shorebirds. Agriculture, Ecosystems and Environment 110:249–56.

Tulare Lake Basin Water Storage District. 1981. Report on irrigation, drainage and flooding in the Tulare Lake Basin. Corcoran, CA, USA.

Waters, T. F. 1977. Secondary production in inland waters. Advanced Ecological Research 10:91–164.

Weis, M. 1938. Tulare Lake history gains interest in relation to present flood situation. The Corcoran Journal, Corcoran, CA, USA.

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