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Invertebrate mercury bioaccumulation in permanent, seasonal, and flooded rice wetlands within California's Central Valley

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ABSTRACT

We examined methylmercury (MeHg) bioavailability in four of the most predominant wetland habitats in California's Central Valley agricultural region during the spring and summer: white rice, wild rice, permanent wetlands, and shallowly-flooded fallow fields. We sampled MeHg and total mercury (THg) concentrations in two aquatic macroinvertebrate taxa at the inlets, centers, and outlets of four replicated wetland habitats (8 wetlands total) during two time periods bounding the rice growing season and corresponding to flood-up and pre-harvest (96 total samples). In general, THg concentrations (mean ± standard error) in Notonectidae (*Notonecta*, back swimmers; $1.18 \pm 0.08\,\mu g\,g^{-1}$ dry weight [dw]) were higher than in Corixidae (*Corisella*, water boatmen; $0.89 \pm 0.06\,\mu g\,g^{-1}$ dw, MeHg: $0.74 \pm 0.05\,\mu g\,g^{-1}$ dw). MeHg concentrations were correlated with THg concentrations in Corixidae ($R^2 = 0.80$) and 88% of THg was in the MeHg form. Wetland habitat type had an important influence on THg concentrations in aquatic invertebrates, but this effect depended on the sampling time period and taxa. In particular, THg concentrations in Notonectidae, but not Corixidae, were higher in permanent wetlands than in white rice, wild rice, or shallowly-flooded fallow fields. THg concentrations in Notonectidae were higher at the end of the rice growing season than near the time of flood-up, whereas THg concentrations in Corixidae did not differ between time periods. The effect of wetland habitat type was more prevalent near the end of the rice growing season, when Notonectidae THg concentrations were highest in permanent wetlands. Additionally, invertebrate THg concentrations were higher at water outlets than at inlets of wetlands. Our results indicate that although invertebrate THg concentrations increased from the time of flood-up to draw-down of wetlands, temporarily flooded habitats such as white rice, wild rice, and shallowly-flooded fallow fields did not have higher THg or MeHg concentrations in invertebrates than permanent wetlands.

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1. Introduction

Recognition of the value of wetlands has led to large-scale efforts worldwide to conserve and restore wetland habitats (Mitsch, 2005). The Central Valley of California has lost over 90% of its historical wetlands to agriculture and urban development (US Fish and Wildlife Service, 1978; Gilmer et al., 1982; Frayer et al., 1989; Dahl, 1990), and large-scale ecosystem restoration of the Central Valley watershed is being implemented with some uncertainties as to the structure of the restored wetland mosaic (http://www.delta.dfg.ca.gov/erp/reports_docs.asp; Moyle et al., 2007; Moyle and Bennett, 2008). Ephemeral wetlands, in particular, are important foraging habitats for waterbirds, because they tend to be highly productive and yield large quantities of seeds and aquatic invertebrates (Krapu and Reinecke, 1992; Anderson and Smith, 2000; Taft et al., 2002; Taft and Haig, 2005). Additionally, ephemerally flooded wetlands, such as river floodplains, are thought to be beneficial for the growth and survival of fishes (Bayley, 1995; Sommer et al., 2001; Jeffres et al., 2008). However, ephemeral wetland habitats also can be more conducive to methylmercury (MeHg) production and bioaccumulation (Hall et al., 1998; Snodgrass et al., 2000; Ullrich et al., 2001), which is the form of mercury (Hg) that is most toxic and biomagnifies up aquatic food chains (Wiener et al., 2003a). California has a legacy of inorganic Hg contamination due to historic Hg mining and gold extraction (Davis et al., 2003; Wiener et al., 2003b), and it is not known whether some wetland habitat types enhance MeHg bioaccumulation more than others.

Among the most abundant ephemeral wetland habitat types in the California Central Valley are agricultural fields, particularly for rice production. Rice fields are shallowly flooded (<30 cm) during the summer for rice growth, and then rice fields often are flooded again post-harvest in fall and winter to speed rice straw decomposition (Bird et al., 2000). Because only 121,000 ha of natural wetlands remain in California after historic losses (US Fish and Wildlife Service, 1978; Gilmer et al., 1982; Frayer et al., 1989; Dahl, 1990), flooded rice fields are significant both numerically, totaling approximately 216,100 ha (U.S. Department of Agriculture, National Agricultural

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Statistics Service, 2007), and ecologically, providing waterbird foraging habitat (Elphick and Oring, 1998; Elphick, 2000). Although agricultural wetlands are among the most abundant wetland habitats in California's Central Valley, bioaccumulation of MeHg in rice fields has not been assessed.

Herein, we examined Hg bioaccumulation within agricultural, seasonal, and permanent wetland habitats common to California's Central Valley during the summer rice growing season. We conducted our study within the Yolo Bypass because it has the highest average annual surface water MeHg concentration of the seven sub-watersheds within the Sacramento–San Joaquin River Delta (Wood et al., 2008). Currently, the California Central Valley Regional Water Quality Control Board is developing a MeHg Total Maximum Daily Load (TMDL) for the Sacramento–San Joaquin River Delta, and the Yolo Bypass may require an 80% reduction in MeHg loadings to meet TMDL goals (Wood et al., 2008). These high MeHg concentrations in the Yolo Bypass may be due in large part to the predominance of wetlands within this sub-watershed (Wood et al., 2008), because wetlands are known to have higher rates of MeHg production than other aquatic habitats (Krabbenhoft et al., 1995; Marvin-DiPasquale et al., 2003; Hall et al., 2008).

Our goal was to evaluate how different wetland management practices influenced MeHg bioaccumulation. We used aquatic invertebrates as our indicator of Hg bioaccumulation, because invertebrates are important food items in wetlands managed for waterbirds (Euliss and Jarvis, 1991; de Szalay et al., 2003) and they are ubiquitous throughout the study wetlands. We examined Hg concentrations in two of the most common invertebrates found in each of the four wetland habitat types: one each from the families Corixidae (*Corisella*, water boatmen) and Notonectidae (*Notonecta*, back swimmers) within the Order Hemiptera. These two invertebrates are known to occupy different trophic positions; *Notonecta* are mostly predatory whereas *Corisella* are considered omnivorous and commonly consume detritus and plant material (Menke, 1979; Polhemus, 1996; Schwiebert, 2007). Thus, we predicted higher Hg concentrations in *Notonecta* than in *Corisella*. Specifically, our objectives were to determine if invertebrate Hg concentrations (1) differed among wetland habitat types, (2) changed during the rice growing season from flood-up to harvest, (3) varied from water inlets to outlets, and (4) differed between invertebrate taxa.

2. Materials and methods

2.1. Study site

We assessed MeHg bioaccumulation within wetlands at the Vic Fazio Yolo Wildlife Area (38.33° N, 121.4° W) in summer 2007. The Yolo Wildlife Area is located within the Yolo Bypass and is managed by the California Department of Fish and Game with the primary goals of restoring wetland habitat, encouraging agriculture, and maintaining the function of the Yolo Bypass for flood control (D. Feliz, California Department of Fish and Game, pers. comm.). The Yolo Bypass is the largest floodplain in the Sacramento–San Joaquin River Delta and provides flood protection as part of the Sacramento River Flood Control Project. It is common for the Yolo Bypass to flood each spring when Sacramento River waters are high due to spring runoff. There are four predominant wetland management strategies during the summer rice growing season: white rice (*Oryza sativa*), wild rice (*Zizania palustris*), permanent wetlands, and shallowly-flooded fallow fields. Both white rice and wild rice are grown extensively throughout the Yolo Wildlife Area and represent the largest wetland area during the late spring and summer. Additionally, former rice fields that are rotated out of production and left fallow for a year are shallowly flooded during the late summer (July–September) to provide foraging habitat for migrating shorebirds. There also are several perennial wetlands that are permanently flooded throughout the year. After the summer rice growing season, both seasonal wetlands and agricultural fields are flooded during the fall and winter to provide habitat for wintering waterfowl and shorebirds.

2.2. Invertebrate sampling

We studied MeHg bioaccumulation within two fields each of white rice, wild rice, permanent wetlands, and shallowly-flooded fallow fields. We sampled two taxa of aquatic macroinvertebrates at the inlets, centers, and outlets of each of the 8 wetlands during two time periods bounding the rice growing season and corresponding to flood-up and pre-harvest (96 total samples). White rice fields were initially flooded, then the water was discharged within two weeks for weed control, and thereafter re-flooded; we conducted our first sampling time period immediately after the fields were re-flooded for rice production. Because fallow fields were managed for migrating shorebirds, they were not initially flooded until late July. Our pre-harvest invertebrate sampling time period occurred immediately before the wild rice harvest in mid September. Thus, our flood-up invertebrate sampling occurred from 25 June to 6 July and our pre-harvest sampling occurred from 28 August to 19 September for all habitats, with the exception that fallow fields were sampled at flood-up on 30 July 2007.

We sampled aquatic invertebrates in the water column and submerged vegetation using D-ring sweep nets with 0.5 mm mesh (diurnal) and floating light traps (nocturnal). Light traps were constructed as described by Marchetti and Moyle (2000), and were set at night and retrieved at dawn the following morning. We also used sweep nets at each site during trap deployment and retrieval to increase the biomass of invertebrates captured. We transported invertebrates from the field in fresh source water on wet ice and stored them in the refrigerator for 24 h to allow the passage of inorganic Hg present in their digestive tracts. We then identified and sorted invertebrates with a dissecting microscope (10×) following Merritt and Cummins (1996); genera were independently confirmed by the R. M. Bohart Museum of Entomology, University of California, Davis. We sampled invertebrates from each site until we reached a biomass of >3 g wet weight each of Corixidae (Order Hemiptera, Family Corixidae, Genus *Corisella*, water boatmen) and Notonectidae (Order Hemiptera, Family Notonectidae, Genus *Notonecta*, back swimmers). We stored invertebrates in Whirl-paks® (Nasco, Modesto, California, U.S.A.) at −20 °C until Hg analysis.

2.3. Mercury determination

Prior to Hg analysis, invertebrates were dried at 60 °C for 24–48 h, then ground and homogenized to a fine powder using a ceramic mortar and pestle. Initially, an aliquot of each Corixidae sample was analyzed for MeHg at Battelle Marine Sciences Laboratory (Sequim, Washington, U.S.A.) using cold vapor atomic fluorescence following EPA method 1630 (U. S. EPA, 2001). We then analyzed the remaining aliquots of the same Corixidae samples and all the Notonectidae samples for total mercury (THg) at the USGS Davis Field Station Mercury Lab, on a Milestone DMA-80 Direct Mercury Analyzer (Milestone Inc., Monroe, Connecticut, U.S.A.) following EPA method 7473 (U. S. EPA, 2000). For 11 invertebrate samples, we could not analyze THg because we were unable to collect enough biomass for both MeHg and THg analyses. Because MeHg and THg were highly correlated (see Results), and the percent MeHg did not vary as a function of THg levels (see Results), we used MeHg concentrations and the average percent MeHg in Corixidae to estimate THg concentrations for those 11 Corixidae samples. Quality assurance measures included analysis of two certified reference materials (either dogfish muscle tissue [DORM-2; National Research Council of Canada, Ottawa, Canada], dogfish liver [DOLT-3; National Research Council of Canada, Ottawa, Canada], or lobster hepatopancreas [TORT-2; National

Research Council of Canada, Ottawa, Canada]), two system and method blanks, two duplicates, one matrix spike, and one matrix spike duplicate per batch. For THg, recoveries (± SE) averaged 106.3 ± 1.7% ($N=9$) and 101.1 ± 1.7% ($N=14$) for certified reference materials and calibration checks, respectively. Matrix spike recoveries for THg averaged 98.3 ± 1.3% ($N=10$), and absolute relative percent difference for all duplicates and matrix spike duplicates averaged 7.5 ± 2.9%. For MeHg, recoveries averaged 91.20 ± 3.8% ($N=3$) for certified reference materials. Matrix spike recoveries for MeHg averaged 97.3 ± 1.8% ($N=12$), and absolute relative percent difference for all duplicates and matrix spike duplicates averaged 7.8 ± 1.6%. We report mean ± standard error THg and MeHg concentrations on a dry weight (dw) basis.

2.4. Statistical analysis

We tested whether THg and MeHg concentrations in invertebrates differed among factors using backward elimination mixed effect analysis of variance (ANOVA), with alpha >0.10 to remove interactions using JMP® version 5.0 (SAS Institute, Cary, North Carolina, U.S.A.). The global mixed model included wetland habitat type (white rice, wild rice, permanent wetland, and fallow fields), site (inlet, center, and outlet), time period (flood-up and pre-harvest), taxa (Corixidae and Notonectidae; for THg model only) as fixed effects, wetland replicate as a random effect, and all 2-way and 3-way interactions of fixed effects. We found significant 2-way interactions for taxa × time period, taxa × wetland type, and time period × wetland type for the THg model, therefore we used conditional *F*-tests (slices) to test the effects of wetland type, time period, and taxa separately while accounting for all the other variables in the model. We then used pairwise *t*-tests to make multiple comparisons. We calculated the proportion of THg in Corixidae that was in the form of MeHg by dividing the MeHg concentration by the THg concentration. We used linear regression to test whether MeHg concentrations were related to THg concentrations in Corixidae, and to test whether THg concentrations in Corixidae were related to THg concentrations in Notonectidae.

3. Results

Across all wetland habitat types and sampling time periods, THg concentrations were 0.89 ± 0.06 μg g^{-1} dw in Corixidae ($N=36$) and 1.18 ± 0.08 μg g^{-1} dw in Notonectidae ($N=45$). Notonectidae THg concentrations were not correlated with Corixidae THg concentrations (linear regression: $N=31$, $R^2=0.01$, $P=0.96$) or Corixidae MeHg concentrations (linear regression: $N=43$, $R^2=0.02$, $P=0.42$) collected at the same locations and time periods. MeHg concentrations in Corixidae were 0.74 ± 0.05 μg g^{-1} dw ($N=46$). Corixidae MeHg concentrations were highly correlated with Corixidae THg concentrations (linear regression: $N=34$, $R^2=0.80$, $P<0.0001$; Fig. 1). In addition, most of the THg in Corixidae was comprised of MeHg (88.0 ± 3.1%) and the proportion of Hg in the form of MeHg was not correlated with THg concentrations (linear regression: $N=34$, $R^2=0.01$, $P=0.99$), indicating that the proportion of THg in the MeHg form did not vary with THg concentrations.

The final model from our backward elimination mixed effect ANOVA model for THg concentrations in invertebrates included wetland type, site, time period, and taxa as fixed effects, wetland replicate as a random effect, and taxa × time period, taxa × wetland type, and time period × wetland type as 2-way interactions (ANOVA: wetland type: $F_{3,3.94}=3.16$, $P=0.15$; site: $F_{2,71.88}=3.84$, $P=0.03$; time period: $F_{1,71.88}=5.12$, $P=0.03$; taxa: $F_{1,71.88}=29.36$, $P<0.0001$; time period × wetland type: $F_{3,71.88}=4.03$, $P=0.01$; taxa × wetland type: $F_{3,71.88}=10.37$, $P<0.0001$; taxa × time period: $F_{1,71.88}=15.83$, $P=0.001$). We therefore used conditional *F*-tests to further interpret the significant interactions to assess whether invertebrate THg concentrations differed among wetlands, taxa, and time periods.

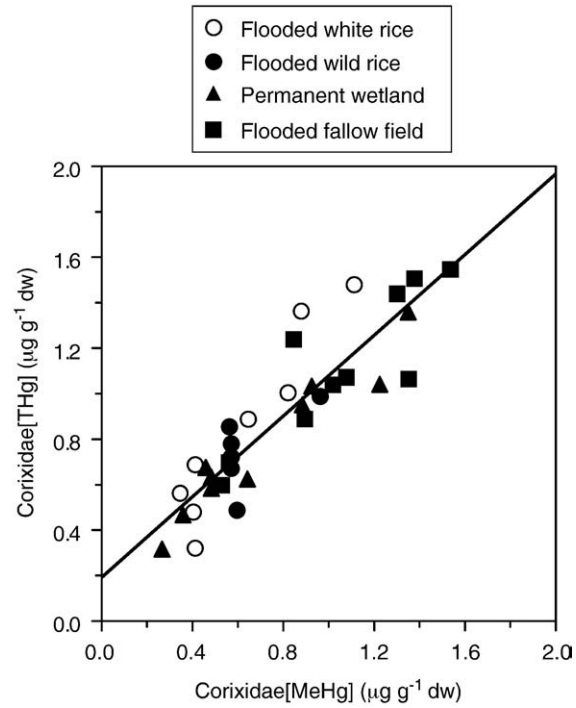

Fig. 1. Corixidae (water boatmen) total mercury (THg) concentrations (μg g^{-1} dry weight) were highly correlated with methylmercury (MeHg) concentrations within California Central Valley wetlands.

3.1. Site

THg concentrations in invertebrates tended to increase from water inlets (least squares mean ± SE: 0.92 ± 0.08 μg g^{-1} dw) and wetland centers (1.01 ± 0.08 μg g^{-1} dw) to water outlets (1.14 ± 0.08 μg g^{-1} dw; Fig. 2). In pairwise comparisons, THg concentrations in invertebrates at the outlet were significantly higher than THg concentrations at the inlets (difference: 0.21 ± 0.08 μg g^{-1} dw; $t_{2,71.89}=2.76$, $P=0.01$) and THg concentrations at wetland centers did not differ from concentrations at inlets (difference: 0.09 ± 0.08 μg g^{-1} dw; $t_{2,71.89}=1.15$, $P=0.25$) nor outlets (difference: 0.12 ± 0.08 μg g^{-1} dw; $t_{2,71.86}=1.61$, $P=0.11$).

3.2. Taxa × Time

THg concentrations in Notonectidae increased from the time of flood-up to pre-harvest (difference: 0.40 ± 0.09 μg g^{-1} dw; $F_{1,71.86}=18.14$, $P<0.0001$), whereas THg concentrations in Corixidae did not differ between time periods (difference: 0.11 ± 0.09 μg g^{-1} dw; $F_{1,71.90}=1.60$, $P=0.21$; Fig. 3). Accordingly, THg concentrations in Corixidae did not differ from Notonectidae during the flood-up time period (difference: 0.09 ± 0.10 μg g^{-1} dw; $F_{1,71.90}=0.94$, $P=0.33$), but Notonectidae were higher than Corixidae during the pre-harvest time period (difference: 0.61 ± 0.09 μg g^{-1} dw; $F_{1,71.86}=48.99$, $P<0.0001$).

3.3. Wetland type × Time

THg concentrations in invertebrates, overall, increased from the time of flood-up to pre-harvest in permanent wetlands (difference: 0.40 ± 0.14 μg g^{-1} dw; $F_{1,71.86}=7.57$, $P=0.01$) and wild rice (difference: 0.29 ± 0.13 μg g^{-1} dw; $F_{1,71.95}=5.19$, $P=0.03$), but not white rice (difference: 0.10 ± 0.12 μg g^{-1} dw; $F_{1,71.86}=0.62$, $P=0.43$) or

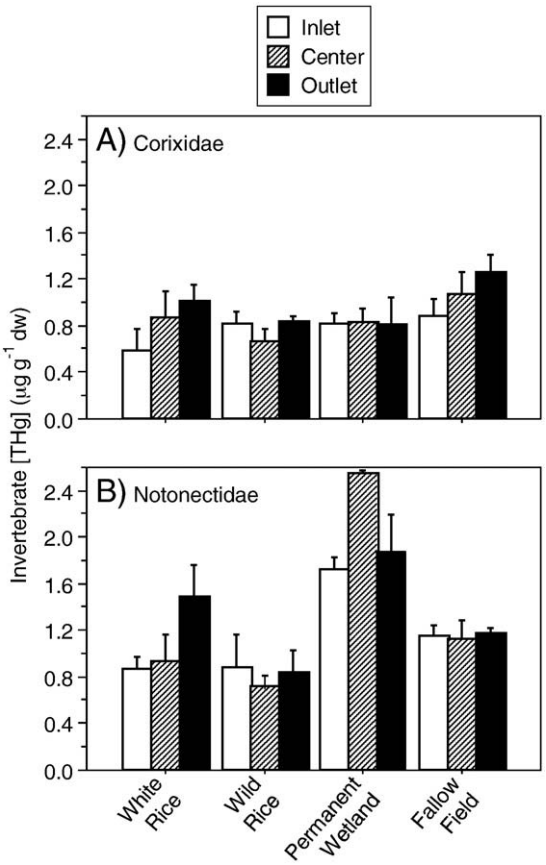

Fig. 2. Total mercury (THg) concentrations (mean ± SE; µg g^{-1} dry weight) in (A) Corixidae (water boatmen) and (B) Notonectidae (back swimmers) at the water inlets (open), centers (shaded), and outlets (solid) of white rice, wild rice, permanent wetland, and shallowly-flooded fallow fields in California's Central Valley.

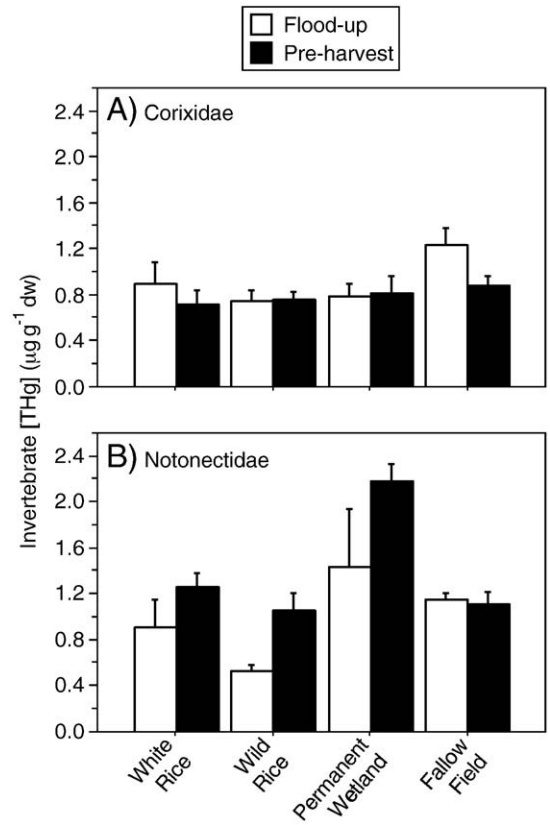

Fig. 3. Total mercury (THg) concentrations (mean ± SE; µg g^{-1} dry weight) in (A) Corixidae (water boatmen) and (B) Notonectidae (back swimmers) among wetland habitat types during time periods corresponding to the flood-up (open) and pre-harvest (solid) of rice in California's Central Valley.

shallowly-flooded fallow fields (difference: 0.20 ± 0.12 µg g^{-1} dw; $F_{1,71.86}$ = 2.54, P = 0.12; Fig. 3). THg concentrations in invertebrates did not significantly differ between wetland habitats within the flood-up time period ($F_{3,6.64}$ = 3.14, P = 0.10; differences: permanent wetland vs white rice: 0.21 ± 0.21 µg g^{-1} dw; permanent wetland vs wild rice: 0.48 ± 0.21 µg g^{-1} dw; fallow vs permanent wetland: 0.09 ± 0.21 µg g^{-1} dw; fallow vs white rice: 0.29 ± 0.20 µg g^{-1} dw; fallow vs wild rice: 0.57 ± 0.20 µg g^{-1} dw; white rice vs wild rice: 0.27 ± 0.20 µg g^{-1} dw) or pre-harvest time period ($F_{3,5.78}$ = 3.78, P = 0.08; differences: permanent wetland vs white rice: 0.51 ± 0.20 µg g^{-1} dw; permanent wetland vs wild rice: 0.59 ± 0.20 µg g^{-1} dw; permanent wetland vs fallow: 0.50 ± 0.20 µg g^{-1} dw; fallow vs white rice: 0.01 ± 0.20 µg g^{-1} dw; fallow vs wild rice: 0.09 ± 0.20 µg g^{-1} dw; white rice vs wild rice: 0.08 ± 0.20 µg g^{-1} dw).

3.4. Wetland type × Taxa

THg concentrations differed among wetland habitats for Notonectidae ($F_{3,6.51}$ = 7.97, P = 0.01). Notonectidae THg concentrations were higher in permanent wetlands than in wild rice (difference: 1.01 ± 0.21 µg g^{-1} dw; $t_{3,6.51}$ = 4.81, P = 0.002), white rice (difference: 0.72 ± 0.21 µg g^{-1} dw; $t_{3,6.51}$ = 3.44, P = 0.01), and fallow fields (difference: 0.67 ± 0.21 µg g^{-1} dw; $t_{3,6.51}$ = 3.19, P = 0.01), but there were no differences between white rice and wild rice (difference: 0.29 ± 0.20 µg g^{-1} dw; $t_{3,6.51}$ = 1.47, P = 0.19), white rice and fallow fields (difference: 0.05 ± 0.20 µg g^{-1} dw; $t_{3,6.51}$ = 0.26, P = 0.80), or wild rice and fallow fields (difference: 0.34 ± 0.20 µg g^{-1} dw; $t_{3,6.51}$ = 1.73, P = 0.14; Figs. 2 and 3). Corixidae THg concentrations did not differ between wetland habitats ($F_{3,5.89}$ = 0.99, P = 0.46; differences: white rice vs permanent wetland: 0.01 ± 0.20 µg g^{-1} dw; permanent wetland vs wild rice: 0.06 ± 0.20 µg g^{-1} dw; fallow vs permanent wetland: 0.25 ± 0.20 µg g^{-1} dw; fallow vs white rice: 0.24 ± 0.20 µg g^{-1} dw; fallow vs wild rice: 0.31 ± 0.20 µg g^{-1} dw; white rice vs wild rice: 0.07 ± 0.20 µg g^{-1} dw). THg concentrations in Notonectidae were higher than Corixidae in permanent wetlands (difference: 1.00 ± 0.14 µg g^{-1} dw; $F_{1,71.86}$ = 48.39, P < 0.0001) and white rice (difference: 0.27 ± 0.12 µg g^{-1} dw; $F_{1,71.86}$ = 4.84, P = 0.03), but THg concentrations in Notonectidae and Corixidae were similar in wild rice (difference: 0.05 ± 0.13 µg g^{-1} dw; $F_{1,71.95}$ = 0.16, P = 0.69) and fallow fields (difference: 0.08 ± 0.12 µg g^{-1} dw; $F_{1,71.86}$ = 0.39, P = 0.53).

3.5. MeHg in Corixidae

Because we used THg concentrations in our main model, we repeated the backward elimination ANOVA model using only the MeHg data in Corixidae and there were no significant interactions. Wetland habitat type, site, and time period were not significant factors influencing MeHg concentrations in Corixidae (ANOVA: wetland type: $F_{3,4}$ = 0.61, P = 0.64; site: $F_{2,37}$ = 1.48, P = 0.24; time period: $F_{1,37}$ = 1.17, P = 0.29; Fig. 4), although Corixidae MeHg concentrations in permanent wetlands and shallowly-flooded fallow fields tended to be elevated (differences: fallow vs white rice: 0.35 ± 0.32 µg g^{-1} dw; fallow vs wild rice: 0.35 ± 0.32 µg g^{-1} dw; permanent wetland vs white rice: 0.24 ± 0.32 µg g^{-1} dw; permanent wetland vs wild rice: 0.24 ± 0.32 µg g^{-1} dw; fallow vs permanent

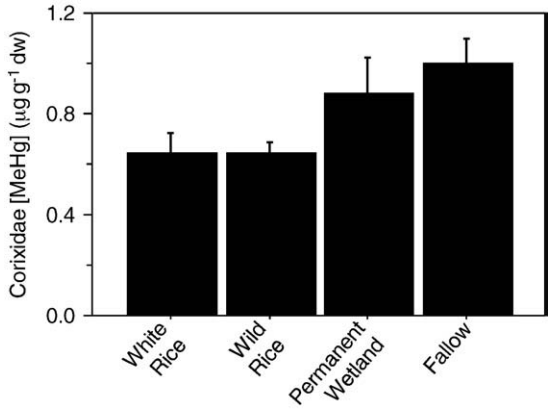

Fig. 4. Methylmercury (MeHg) concentrations (mean ± SE; μg g^{-1} dry weight) in Corixidae (water boatmen) within white rice, wild rice, permanent wetland, and shallowly-flooded fallow fields in California's Central Valley.

wetland: 0.12 ± 0.32 μg g^{-1} dw; wild rice vs white rice: 0.01 ± 0.32 μg g^{-1} dw).

4. Discussion

The Yolo Wildlife Area, like many other state and federal refuges in California's Central Valley, is primarily managed as waterfowl and shorebird habitat. Therefore, wetlands are typically managed using shallow and intermittent flooding because seasonal wetlands typically have greater invertebrate abundance than permanent wetlands with longer hydroperiods (Neckles et al., 1990). In particular, reverse-cycle seasonal wetlands are intermittently flooded during the spring and summer to increase invertebrate production for breeding ducks (Neckles et al., 1990; de Szalay et al., 2003), which switch from a diet primarily of seeds to that of mainly invertebrates in order to attain the required protein for egg formation (reviews by Alisauskas and Ankney, 1992; Krapu and Reinecke, 1992), and ducklings, which require invertebrate protein for rapid growth (review by Sedinger, 1992). Unfortunately, periodic wetting and drying of wetland habitats often is associated with increased MeHg production and concentrations in biota (Hall et al., 1998; Snodgrass et al., 2000; Ullrich et al., 2001).

We found that wetland habitat type had an important influence on THg concentrations in invertebrates, but this effect depended on the sampling time period and taxa. In particular, temporarily flooded habitats did not have higher THg or MeHg concentrations in invertebrates than permanent wetlands. Instead, THg concentrations in Notonectidae were higher in permanent wetlands than in white rice, wild rice, or shallowly-flooded fallow fields, whereas there was no difference among wetland types for THg or MeHg concentrations in Corixidae. THg concentrations in Notonectidae, but not Corixidae, increased from the time of flood-up to draw-down of wetlands. The effect of habitat was more prevalent at the end of the rice growing season, when Notonectidae THg concentrations were highest in permanent wetlands. Similarly, THg concentrations in amphipods (Crangonyctidae) were highest in permanent wetlands compared to intermittently flooded sites in the Okefenokee Swamp in Georgia (George and Batzer, 2008).

Importantly, our results are in contrast to a companion study we conducted simultaneously in which we used both caged fish (western mosquitofish, *Gambusia affinis*) and wild fish (western mosquitofish and Mississippi silversides, *Menidia audens*) to assess MeHg bioaccumulation in wetland fishes. In that study, we found strong evidence for higher THg concentrations and body burdens in both caged and wild fish in white rice and wild rice fields compared to fish in permanent wetlands (J. T. Ackerman, U. S. Geological Survey, unpublished data). However, we found similar results in that both invertebrate and fish THg concentrations were higher at water outlets than at inlets of wetlands, suggesting that inorganic Hg became methylated, concentrated, and transported in the direction of water flow. These incongruent results for THg concentrations in invertebrates and fish among wetland habitats indicate that bioaccumulation pathways in wetlands are complex and underscore the importance of using several taxa at different trophic levels to examine MeHg bioaccumulation in wetlands. The complexity of MeHg bioaccumulation in wetlands is further illustrated by the fact that we did not find a correlation between THg concentrations in Notonectidae and Corixidae, even though the paired samples were collected at the same sites and on the same days. Notonectidae (*Notonecta*) typically forage at a higher trophic level than Corixidae (*Corisella*; Menke, 1979; Merritt and Cummins, 1996). Thus, the lack of correlation between their THg concentrations indicates that they foraged on different prey items and that the two invertebrates were not tightly linked within the foodweb.

As in other studies of wetland invertebrates (e.g., George and Batzer, 2008), we found that THg concentrations in invertebrates differed among taxa. THg concentrations in Notonectidae tended to be higher than in Corixidae, especially at the end of the rice growing season and in permanent wetland habitats. Both Notonectidae (mean THg: 1.18 μg g^{-1} dw) and Corixidae (mean THg: 0.89, mean MeHg: 0.74 μg g^{-1} dw) Hg concentrations at the Yolo Wildlife Area were considered high when compared to invertebrates in other wetlands. For example, MeHg concentrations in experimentally flooded Ontario wetlands averaged 0.12 to 0.32 μg g^{-1} dw in Corixidae and 0.16 to 0.44 μg g^{-1} dw in Notonectidae (Hall et al., 1998). Corixidae THg concentrations in Portugal saltpan wetlands were 0.03 to 0.15 μg g^{-1} dw (Tavares et al., 2008). Notably, Corixidae THg and MeHg concentrations were higher at the Yolo Wildlife Area wetlands than in wetlands located downstream within the same watershed in San Francisco Bay (THg: 0.63 μg g^{-1} dw, MeHg: 0.59 μg g^{-1} dw; A. K. Miles, U. S. Geological Survey, unpublished data).

Considering that 75% and 48% of all Corixidae samples at the Yolo Wildlife Area exceeded reported MeHg dietary effect levels of 0.50 μg g^{-1} dw for mallard reproduction (*Anas platyrhynchos*; Heinz, 1979) and 0.70 μg g^{-1} dw for American kestrel reproduction (*Falco sparverius*; Albers et al., 2007), respectively, and that Corixidae are common in waterfowl diets (Euliss and Jarvis, 1991), higher trophic level predators may be at risk to current Hg concentrations in prey within Yolo Bypass wetlands. For example, within San Francisco Bay, we found that black-necked stilt chicks (*Himantopus mexicanus*) found dead near nesting sites had higher THg concentrations in down feathers than those in randomly-sampled live chicks of similar age (Ackerman et al., 2008) and that failed-to-hatch Forster's tern (*Sterna forsteri*) eggs had higher THg concentrations than randomly-sampled live eggs (Ackerman and Eagles-Smith, 2008). Similar deleterious effects of Hg on waterbird reproduction may be occurring within Yolo Bypass wetlands where Hg concentrations in prey are considerably higher than in San Francisco Bay wetlands. In fact, MeHg concentrations in Yolo Bypass invertebrates were substantially higher than the Sacramento–San Joaquin River Delta TMDL benchmark MeHg concentration for small fish (0.03 μg g^{-1} ww, or approximately 0.11 μg g^{-1} dw assuming 73% moisture [J. T. Ackerman, U. S. Geological Survey, unpublished data]) that is meant to be protective of wildlife (Wood et al., 2008). Thus, there may be substantial risk of MeHg toxicity to waterbirds and other wildlife that forage in Yolo Bypass wetlands and MeHg concentrations in waterbirds should be evaluated.

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