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Dissolved oxygen under waterhyacinth following herbicide application

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ABSTRACT

The California State Parks Division of Boating and Waterways (CDBW) manages waterhyacinth [*Eichhornia crassipes* (Mart.) Solms] in the Sacramento–San Joaquin River Delta (the Delta) to ensure navigation and fish habitat. Decreasing the amount of waterhyacinth in the Delta should increase the proportion of oxygenated water for fish habitat and migration. However, some water resource management personnel are concerned that plant decomposition following herbicide treatment could temporarily lower the dissolved oxygen in the water under the plant canopy. The U.S. Department of Agriculture Agricultural Research Service and CDBW conducted an experiment in the summer of 2016 to monitor dissolved oxygen following herbicide treatment relative to untreated waterhyacinth canopies and open water. The experiment was conducted in two Delta environments. The first consisted of channels subject to tidal fluctuations and mass flow, and the second consisted of back-end sloughs, which have only a single outlet, where there was minimal water movement. Three channel-side sites were chosen and three 0.025-ha plots per site were randomly assigned to be treated with glyphosate or 2,4-D, or remain untreated. Three back end slough sites were chosen and three 0.25-ha plots per site were randomly assigned to be treated with imazamox, glyphosate, or 2,4-D, or remain untreated. A data logger measuring dissolved oxygen every 30 min was deployed under the canopy in each plot. Data was collected 2 wk prior to treatment through 6 wk after treatment. Data loggers were also deployed in the open water, away from waterhyacinth canopy, in the channels and in the back-end sloughs. The dissolved oxygen under waterhyacinth was consistently lower than in the open water. The dissolved oxygen levels pre- and posttreatment were compared for each treatment, using ANOVA ($P \leq 0.05$). For the channel-side trial, there was no significant difference in dissolved oxygen levels for any of the treatments ($P > 0.18$). In the back-end sloughs, there was no significant difference in dissolved oxygen levels for any of the treatments ($P > 0.92$ for all comparisons). Herbicide treatments did not result in a significant decline in dissolved oxygen after treatment relative to pretreatment levels.

Keywords: 2,4-D, dissolved oxygen depletion, *Eichhornia crassipes*, glyphosate, imazamox, tidal flow

INTRODUCTION

Waterhyacinth [*Eichhornia crassipes* (Mart.) Solms] is a floating aquatic perennial macrophyte native to the Amazon region in South America. It is a monocot and a member of the Pontederiaceae family. In the United States, waterhyacinth has become invasive across the Southeast and the Gulf Coast, and in California. The first recorded introduction of waterhyacinth into the United States was prior to 1890 for use as an ornamental in ponds (Penfound and Earle 1948, Owens and Madsen 1995). It was first reported in California in Yolo County in 1904 (Bock 1968) and has become a widespread invasive species in the Sacramento–San Joaquin River Delta (hereafter the Delta). It is estimated to cover approximately 1,214 ha (3,000 ac) in the Delta (Ta et al. 2017).

Waterhyacinth has a number of negative impacts on invaded water bodies, one of which is decreased dissolved oxygen. Dissolved oxygen in the water column is needed by aerobic organisms, such as fish, aquatic invertebrates, and aquatic plants. The amount that fish need to survive depends on the water temperature. Dissolved oxygen below 2.5 mg L^{-1} is considered hypoxic (Turner et al. 2010) and 5.0 mg L^{-1} is used as a threshold below which warm-water fish will exhibit avoidance behaviors (CDBW 2001, Newcomb and Pierce 2010). Many fish species have species-specific avoidance thresholds, below which densities of that species decline sharply. As different species' thresholds vary, total fish abundance, as well as species richness, declines gradually as dissolved oxygen levels decrease (Breitburg 2002). For salmonids, which migrate through the Delta between spawning regions and the Pacific Ocean, low dissolved oxygen leads to reduced growth, reduced spawning success, reduced fecundity, and reduced swimming performance (Newcomb and Pierce 2010).

There are many factors which can influence the level of dissolved oxygen in the water column, including water flow, reaeration, temperature, wind, precipitation, and the biota present in the water. Floating aquatic vegetation, such as waterhyacinth, can lower the amount of dissolved oxygen in the water column below them. Floating macrophytes limit light penetration into the water, thereby limiting photosynthesis by submersed plants or algae. Dense growth of floating leaves may inhibit gas exchange between the air and water. The dissolved oxygen content of the water column

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under waterhyacinth is generally lower than in open water or in the presence of any other floating or submersed macrophytes (Madsen 1997, Toft 2000). Dense vegetation, in general, reduces dissolved oxygen in the subcanopy, reduces water flow rates, and may increase water temperature (Frodge et al. 1990, Carter et al. 1991).

Because the level of dissolved oxygen under waterhyacinth canopies is lower than in open water (Toft 2000), decreasing the amount of waterhyacinth in the Delta should increase the available acreage of fast-moving, highly oxygenated water available for fish habitat and migration. In 1982, the California State Parks Division of Boating and Waterways (CDBW) was designated as the lead agency for controlling waterhyacinth in the Delta, its tributaries, and the Suisun Marsh. In 2001, in consultation with the U.S. Fish and Wildlife Service and the National Marine Fisheries Service, CDBW implemented a fish passage protocol to ensure that impacts on fish habitat and migration are factored into waterhyacinth management activities, such as herbicide application (CDBW 2001). CDBW primarily used glyphosate and 2,4-D to treat waterhyacinth and other invasive floating macrophytes. In 2016, they treated 1,354 ha with glyphosate (78% of the total herbicide used for floating aquatic vegetation) and 376 ha with 2,4-D (22%). Imazamox (0.04%) and penoxsulam (0.01%) were used to treat 6 ha and 2 ha, respectively (CDBW 2017).

As CDBW works to decrease the acreage of waterhyacinth in the Delta, some resource managers are concerned that plant decomposition following herbicide treatment may temporarily lower the dissolved oxygen in the water under the plant canopy. We undertook a study in 2016 to monitor dissolved oxygen as waterhyacinth plants decomposed following herbicide treatment, and to compare this to the dissolved oxygen levels under untreated waterhyacinth canopies and in open water.

MATERIALS AND METHODS

In the summer of 2016, we implemented an experiment designed to measure dissolved oxygen under waterhyacinth mats treated with herbicides. The study was conducted in two types of areas: one investigating channel-side sites, with high water exchange, and the second investigating back-end slough areas, with limited water exchange. For the channel-side area type, three sites were chosen within the Delta in California: Connection Slough (38°00′36.098″N; 121°33′19.106″W), Old River (38°01′1.966″N; 121°33′47.339″W), and Holland Cut (38°01′26.709″N; 121°34′57.173″W). Within each site, three 30.5 by 9.1–m (100 by 30 ft; 0.025 ha) treatment plots were measured and marked using polyvinyl chloride poles driven into the benthic soil at the corners of each plot. The three plots within each site were randomly assigned to be treated with glyphosate, treated with 2,4-D, or remain untreated as reference plots. A PME miniDO$_2$T Logger[1] was deployed under each treatment plot on June 2, 2016. Each miniDO$_2$T Logger was suspended in the water column 0.5 m below the surface, between a weighted anchor and a buoy. Within each site, a miniDO$_2$T Logger was also deployed in the open water, 500 to 1,000 m away from the waterhyacinth mats. Dissolved oxygen was recorded by each logger at 30-min intervals, until the loggers were collected on 27 July 2016. The same protocol was followed for the back-end slough trial at three sites: Rhode Island (38°00′3.209″N; 121°34′28.103″W), Trapper Slough (37°54′42.908″N; 121°27′6.629″W), and Sevenmile Slough (38°06′40.545″N; 121°36′51.360″W), except that an additional herbicide, imazamox, was tested, in addition to 2,4-D and glyphosate. The miniDO$_2$T Loggers were deployed on 6 June 2016 for the back-end slough trial.

On 16 June and 17 June 2016, CDBW staff applied herbicides to the treatment plots, following standard application protocol. Glyphosate (1,376 g ha^{-1} [120 oz ac^{-1}])[2], 2,4-D (734 g ha^{-1})[3], and imazamox (367 g ha^{-1})[4] were applied from a boat or land-based sprayer using a handgun sprayer at 50 gallons per acre (GPA). All herbicide treatments also included a crop oil concentrate at 1% v/v (10 ml L^{-1})[5]. The reference plots received no herbicide treatment and the water around the miniDO$_2$T Logger in the open water at each site was untreated.

Data from the loggers were downloaded for 40 d after treatment (DAT). For the channel-side sites, 2 of the 12 deployed loggers were lost during the study. The logger deployed in the open water at Site 2 was downloaded through 30 June, but was lost after that. At Site 3, the logger at the untreated plot went missing, and was replaced with logger from the open-water Site 3 on 23 June 2016. For the back-end slough sites, one of the open water loggers was lost before data could be downloaded.

The data were imported into Microsoft Excel 2016, where hourly mean, daily mean, daily maximum, and daily minimum dissolved oxygen were calculated. In R (v3.3.2, R Core Team 2016), ANOVA was performed for the daily mean dissolved oxygen, daily maximum dissolved oxygen, and daily minimum dissolved oxygen, on a weekly basis from 2 June through 27 July 2016. All the daily means from the first week were compared to the rest of the daily means from that week, and the same was done for each subsequent week. The same procedure was done for each week's daily maximums and daily minimums. There were a total of two pretreatment weeks and six posttreatment weeks. Two-way comparisons were used between each of the groups. These comparisons used the differences in least square means to determine if there was a significant difference between means of the two groups ($\alpha = 0.05$) using Tukey's Honest Significant Difference. For each two-way comparison, the H_0 was that there was no significant difference between the means of the two groups. When the treatments were randomized within each plot, the dissolved oxygen levels showed preexisting variability across the treatments. The goal of this study was to determine the effect that herbicide treatments had on the dissolved oxygen levels. To separate the posttreatment effects from the preexisting variation, the ratio between the mean within each treatment and the mean across all the plots for the pretreatment period was calculated and each posttreatment measurement was adjusted by multiplying by these ratios.

Pretreatment and posttreatment daily mean dissolved oxygen levels were compared by treatment to see if the treatment caused a significant increase or decrease in dissolved oxygen levels. The pretreatment and posttreatment percentage of time below 5.0 mg L^{-1} of dissolved oxygen was compared by treatment.

RESULTS AND DISCUSSION

Channel-side pretreatment

The dissolved oxygen content measured in the open water had a daily mean ± SD of 7.47 ± 0.31 mg L^{-1} from 2 June through 15 June 2016, the period prior to treatment. These open-water areas had higher average dissolved oxygen and less variability than the water under canopies of waterhyacinth, which had a daily mean ± SD of 5.96 ± 1.17 mg L^{-1} for the same pretreatment period. Comparisons of daily mean, maximum, and minimum dissolved oxygen were done pretreatment and posttreatment (Figure 1).

For the ANOVA comparing the daily mean for open-water plots, pretreatment glyphosate plots, pretreatment 2,4-D plots, and untreated plots (Figure 1), the H_0 of no difference between the means of any treatments was rejected ($P < 0.0001$). The open-water plots had significantly higher dissolved oxygen ($P < 0.0001$) than any of the vegetated plots (glyphosate, 5.32 mg L^{-1}; 2,4-D, 6.19 mg L^{-1}; untreated, 6.55 mg L^{-1}). The untreated and 2,4-D plots showed no difference ($P = 0.3651$), while the plots which were later treated with glyphosate had significantly lower dissolved oxygen than the untreated ($P < 0.0001$) or plots that were later treated with 2,4-D ($P = 0.0002$). This pretreatment difference was due to natural variation among the plots, rather than an effect of a treatment.

Most of the comparisons showed no difference for daily maximum dissolved oxygen prior to treatment (Figure 1). The comparisons that did show a significant difference were glyphosate (7.64 mg L^{-1}) when compared with the untreated plots (8.75 mg L^{-1}, $P = 0.0002$) and glyphosate compared to open water (8.28 mg L^{-1}, $P = 0.0346$).

For the daily minima, the open-water plots (6.65 mg L^{-1}) were significantly higher than untreated (3.54 mg L^{-1}, $P < 0.0001$), glyphosate (1.93 mg L^{-1}, $P < 0.0001$), and 2,4-D (2.88 mg L^{-1}, $P < 0.0001$). Based on these minimum levels of oxygen in the water, it is likely that fish would choose the open-water areas over the waterhyacinth mats. The plots later treated with glyphosate were significantly lower than the untreated plots ($P = 0.0013$).

Channel-side treatment

The herbicide applications occurred on 16 and 17 June. Over this 2-d period, the open-water plots had a mean dissolved oxygen of 7.95 mg L^{-1}, with an average maximum of across the plots of 8.90 mg L^{-1} and an average minimum of an average 7.25 mg L^{-1}. The untreated plots had a mean dissolved oxygen of 6.68 mg L^{-1}, with an average maximum of across the plots of 8.94 mg L^{-1} and an average minimum of an average 2.47 mg L^{-1}. The glyphosate plots had a mean dissolved oxygen level of 5.49 mg L^{-1}, with an average maximum of across the plots of 9.04 mg L^{-1} and an average minimum of an average 1.19 mg L^{-1}. The 2,4-D plots had a mean dissolved oxygen of 6.65 mg L^{-1}, with an average maximum of across the plots of 8.41 mg L^{-1} and an average minimum of an average 2.76 mg L^{-1}. These values, very similar to the pretreatment values, were separated from both the pretreatment and posttreatment values so they didn't influence either analysis.

Channel-side posttreatment

From pretreatment to posttreatment, the mean dissolved oxygen increased slightly in open water (from 7.47 to 7.70 mg L^{-1}), 2,4-D plots (from 6.19 to 6.31 mg L^{-1}), and glyphosate plots (from 5.32 to 5.53 mg L^{-1}). The untreated plot, by contrast, had a decrease in mean dissolved oxygen of 0.82 mg L^{-1}, from 6.55 to 5.73 mg L^{-1} from pretreatment to posttreatment. The untreated plots present a baseline against which the treated plots can be compared. Waterhyacinth grows rapidly during the summer months when the trial took place, and left unchecked, the dissolved oxygen decreased under the untreated plots. The treated plots did not have this decrease, and actually had slightly higher dissolved oxygen after treatment.

In the 2,4-D plots, by 2 wk after treatment (WAT), most of the leaves were necrotic and brittle, with some exhibiting epinasty. Some of the plants were prostrate on the water surface. The plots were less dense due to some of the plants sinking as they died or parts of the plants being carried off by the water. By 4 WAT, most of the petioles were lodged on the water surface and some more plant material had either decayed or been carried away by the water current. Some transient floating mats of waterhyacinth were observed in areas of the plots that had only dead floating leaves remaining. By 6 WAT, most of the plots were clear of the treated waterhyacinth, but new waterhyacinth mats and waterprimrose (*Ludwigia* spp.) appeared to be colonizing the habitat.

In the glyphosate plots, at 2 WAT, some leaves were beginning to show necrosis, but the leaves remained upright and the canopy structure remained intact. By 4 WAT, areas of the plots had become cleared of waterhyacinth, while other areas had necrotic leaves still standing upright. By 6 WAT, in glyphosate plots, there are some scattered petioles floating on the water surface, along with some necrotic plants that remained alive. There are also some newly arrived waterhyacinth mats beginning to recolonize the cleared area. The untreated plots remained densely populated with waterhyacinth.

The open-water plots had much higher mean daily dissolved oxygen (7.70 mg L^{-1}) than any of the vegetated plots posttreatment. The means for each day from the 6-wk posttreatment period were compared to the daily means from all the treatments. The glyphosate plots had the lowest mean daily dissolved oxygen (5.53 mg L^{-1}), though they were no different than the untreated plots (5.73 mg L^{-1}, $P = 0.6283$). Posttreatment, the 2,4-D plots (6.31 mg L^{-1}) had significantly higher dissolved oxygen than either the untreated plots ($P = 0.0021$) or the glyphosate plots ($P < 0.0001$).

The open-water plots had higher maximum daily dissolved oxygen (9.14 mg L^{-1}) than any of the vegetated plots posttreatment. Unlike for mean dissolved oxygen,

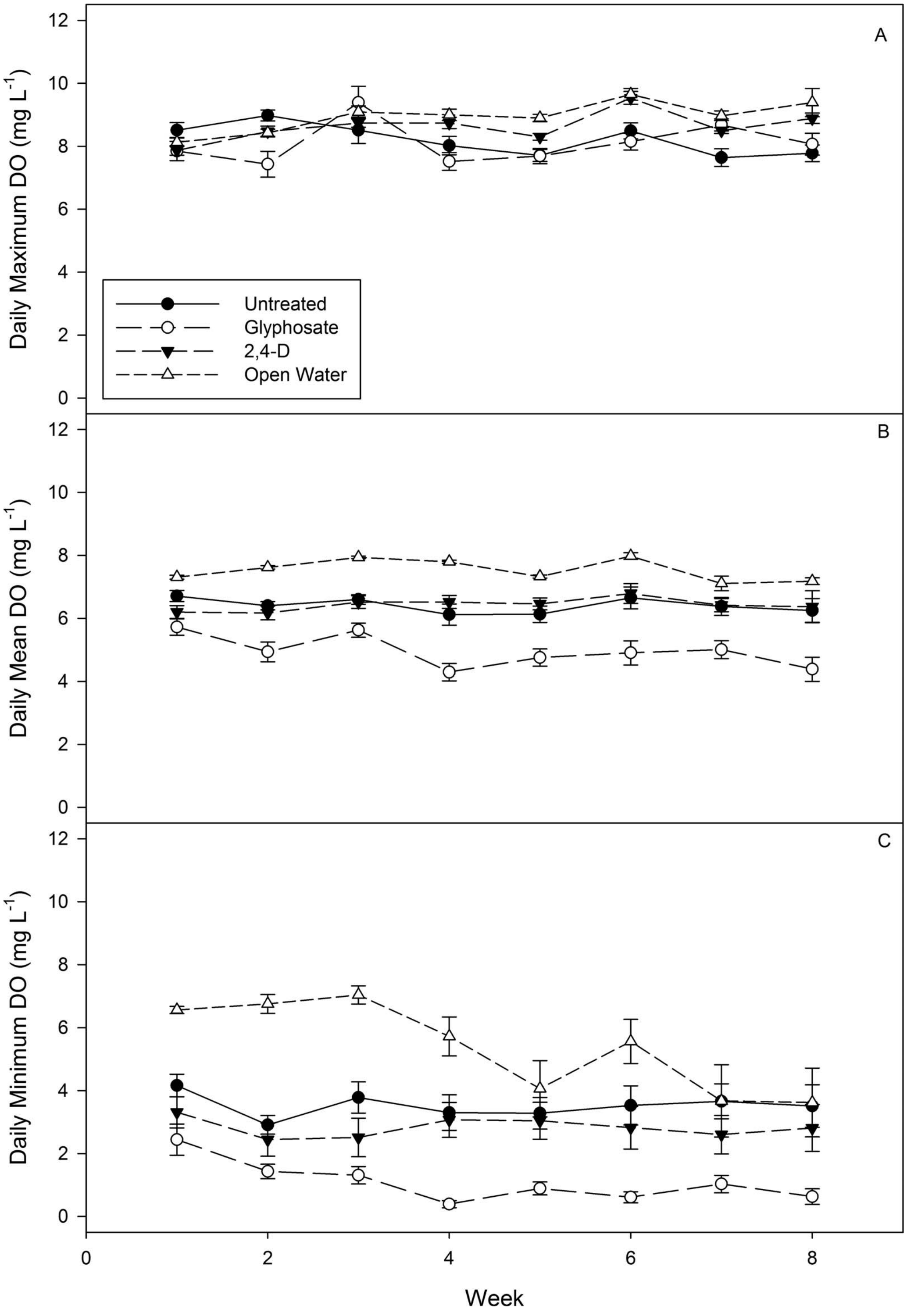

Figure 1. Channel-side trial: (A) daily maximum dissolved oxygen for each treatment, (B) daily mean dissolved oxygen for each treatment, and (C) daily minimum dissolved oxygen for each treatment. Treatments occurred at the end of Week 2. Error bars represent standard errors of the means.

both the glyphosate maximum (8.85 mg L^{-1}) and 2,4-D maximum (8.79 mg L^{-1}) were closer to the open-water plots than the untreated plots (7.42 mg L^{-1}). The untreated daily maxima were significantly lower than each of the other treatments ($P < 0.0001$). The 2,4-D and glyphosate plots show no difference between them ($P = 0.9770$) and neither is different from the open-water daily maxima ($P = 0.2122$ for 2,4-D and $P = 0.3807$ for glyphosate).

All the treatments had daily minima for dissolved oxygen decline from the pretreatment period to the posttreatment period. The open water declined the most, from 6.65 to 5.56 mg L^{-1}. The daily minima in the posttreatment period still

Table 1. Percentage of mean dissolved oxygen levels below 5.0 mg L^{-1} before and after treatment in the channel-side and back-end slough trials. A value of 50.0% would represent that dissolved oxygen was below 5.0 mg L^{-1} half of the time and above 5.0 mg L^{-1} half of the time.

Treatment	Pretreatment (2–16 June 2016)	Posttreatment (17 June–27 July 2016)	Difference Between Pretreatment and Posttreatment
Channel-side			
Open water	0.2%	1.0%	+0.8%
Untreated	15.5%	30.3%	+14.7%
2,4-D	21.0%	15.9%	−5.1%
Glyphosate	42.3%	46.7%	+4.4%
Back-end slough			
Open water	50.2%	55.0%	+4.8%
Untreated	99.7%	96.0%	−3.7%
Imazamox	92.0%	86.9%	−5.1%
2,4-D	89.7%	80.4%	−9.4%
Glyphosate	87.1%	81.9%	−5.2%

averaged above the 5.0-mg L^{-1} threshold for fish avoidance in the open water. The untreated plots declined 0.93 mg L^{-1}, from 3.54 to 2.61 mg L^{-1}; the glyphosate plots declined 0.65 mg L^{-1}, from 1.93 to 1.28 mg L^{-1}; and the 2,4-D plots declined 0.22 mg L^{-1}, from 2.88 to 2.66 mg L^{-1}. The open-water plots were significantly higher than each of the other treatments ($P < 0.0001$). The posttreatment glyphosate minima were significantly lower than the untreated plots ($P = 0.0013$) and lower than the 2,4-D plots without showing significance ($P = 0.0667$).

When pretreatment dissolved oxygen was compared to posttreatment dissolved oxygen for each treatment, there was no significant difference in dissolved oxygen levels for any of the treatments ($P = 0.1761$). The herbicide treatments did not affect the plots in a way that caused the dissolved oxygen to increase or decrease significantly when compared to the same plots pretreatment.

A dissolved oxygen level of 5.0 mg L^{-1} is a stress threshold for fish, below which they will exhibit avoidance behaviors (CDBW 2001, Newcomb and Pierce 2010). In the open-water plots (Table 1), dissolved oxygen went below 5.0 mg L^{-1} for 0.2% of the time from 2 June to 16 June and for 1.0% of the time from 17 June to 27 July. The open-water areas had minimal time below 5.0 mg L^{-1}, and provided an area for fish migration and habitat. From 2 June to 16 June, in the pretreatment period, the dissolved oxygen under the waterhyacinth canopies went below 5.0 mg L^{-1} for 27.4% of the time. Posttreatment, the herbicide treatment plots either had less time below 5.0 mg L^{-1} or had a much smaller increase than the untreated plots. From 17 June to 27 July, in the period after the herbicide plots were treated, the percentage of time below 5.0 mg L^{-1} in the untreated plots nearly doubled, from 15.5 to 30.3% (a 94.8% increase). The glyphosate plots increased from 42.3 to 46.7% (a 10.4% increase), while the 2,4-D plots decreased from 21.0 to 15.9% (a 24.4% decrease).

Back-end sloughs pretreatment

There is far less water movement in the back-end sloughs than there is in channels and the dissolved oxygen is much lower. In the open-water areas of the back-end sloughs, there was a daily mean ± SD of 3.91 ± 1.11 mg L^{-1}; fish have been found to exhibit avoidance below 5.0 mg L^{-1} (Newcomb and Pierce 2010). For the ANOVA comparing the daily mean for open-water plots, pretreatment glyphosate plots, pretreatment 2,4-D plots, pretreatment imazamox plots, and untreated plots (Figure 2), the H_0 of no difference between the means of any treatments was rejected ($P < 0.0001$). The open-water plots had significantly higher dissolved oxygen than any of the vegetated plots ($P < 0.0001$ compared to the untreated [0.42 mg L^{-1}] or imazamox [1.68 mg L^{-1}] plots, $P = 0.0005$ compared to the 2,4-D plots [1.97 mg L^{-1}], and $P = 0.0010$ compared to the glyphosate plots [0.42 mg L^{-1}]). The untreated plots had significantly lower mean dissolved oxygen than the other vegetated plots in the pretreatment period ($P = 0.0024$ for 2,4-D, $P = 0.0013$ for glyphosate, and $P = 0.023$ for imazamox). Since these levels were measured before the treatments, the difference in mean dissolved oxygen was due to natural variation among the plots, rather than an effect of a treatment.

For the daily maximum dissolved oxygen values in the pretreatment back-end slough (Figure 2), the untreated plots (1.51 mg L^{-1}) were much lower than the other plots and the open water (6.11 mg L^{-1}). The average daily maxima for the pretreatment glyphosate plots (4.24 mg L^{-1}), 2,4-D plots (4.13 mg L^{-1}), and imazamox plots (3.78 mg L^{-1}) were all below the threshold for fish avoidance. Collectively, the dissolved oxygen was below 5.0 mg L^{-1} for 92.2% of the time under the waterhyacinth canopies (Table 1). With so much of the time below 5.0 mg L^{-1}, most warm-water fish would likely avoid these back-end areas almost all the time.

The minima for all the pretreatment back-end slough dissolved oxygen measurements were below 1.0 mg L^{-1}, (untreated at 0.12 mg L^{-1}, glyphosate at 0.53 mg L^{-1}, 2,4-D at 0.75 mg L^{-1}, and imazamox at 0.67 mg L^{-1}). Open-water areas of the back-end sloughs had 2.68 mg L^{-1}.

Back-end sloughs treatment

The herbicide applications occurred on 16 and 17 June 2016. Over this 2-d period, the open-water plots had a mean dissolved oxygen of 4.07 mg L^{-1}, with an average maximum of across the plots of 6.77 mg L^{-1} and an average minimum of an average 3.33 mg L^{-1}. The untreated plots had a mean dissolved oxygen of 0.21 mg L^{-1}, with an average maximum of across the plots of 1.81 mg L^{-1} and an average minimum of an average 0.08 mg L^{-1}. The glyphosate plots had a mean dissolved oxygen of 2.81 mg L^{-1}, with an average maximum of across the plots of 5.55 mg L^{-1} and an average minimum of an average 0.09 mg L^{-1}. The 2,4-D plots had a mean dissolved oxygen of 2.63 mg L^{-1}, with an average maximum of across the plots of 6.21 mg L^{-1} and an average minimum of an average 1.22 mg L^{-1}. These values, very similar to the pretreatment values, were separated from both the pretreatment and posttreatment values so they didn't influence either analysis.

Back-end sloughs posttreatment

The open-water mean dissolved oxygen decreased from the pretreatment to the posttreatment periods, from 3.91 to

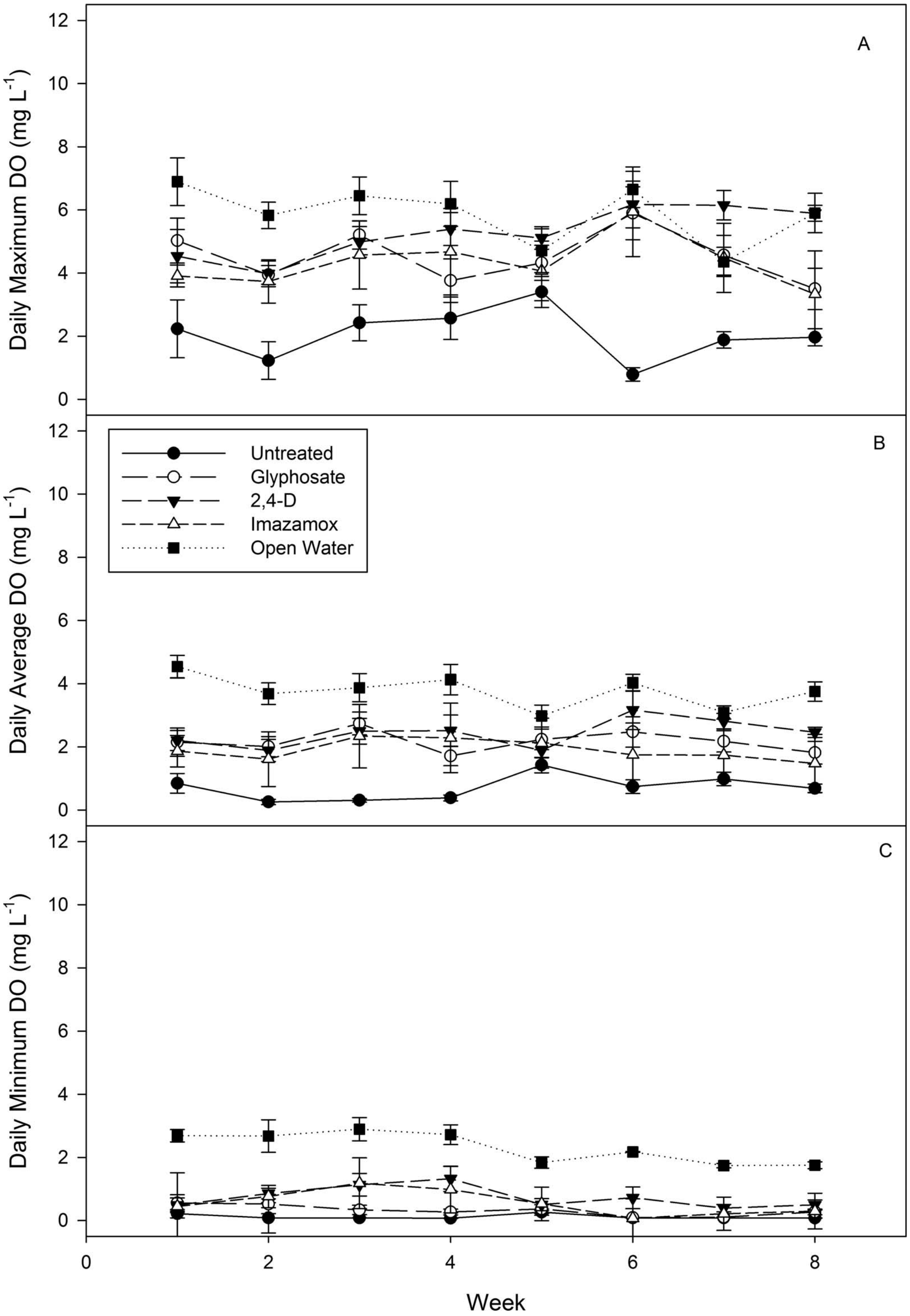

Figure 2. Back-end slough trial: (A) daily maximum dissolved oxygen for each treatment, (B) daily mean dissolved oxygen for each treatment, and (C) daily minimum dissolved oxygen for each treatment. Treatments occurred at the end of Week 2. Error bars represent standard errors of the means.

3.64 mg L^{-1}. All the vegetated plots increased posttreatment, including the untreated plots, with the values ranging from 0.76 to 2.56 mg L^{-1}.

The open-water maximum dissolved oxygen decreased from the pretreatment to the posttreatment periods, from 6.11 to 5.70 mg L^{-1}. All the vegetated plots increased from the pretreatment period, to 2.18 mg L^{-1} for untreated, to 4.57 mg L^{-1} for glyphosate, to 4.54 mg L^{-1} for imazamox, and to 5.61 mg L^{-1} for 2,4-D. Though the daily maxima for the 2,4-D plots did increase from 1.48 to

5.61 mg L^{-1}, they remained below 5.0 mg L^{-1} for 80.4% of the time (Table 1).

The minima for all the posttreatment back-end slough dissolved oxygen measurements were below 1.0 mg L^{-1}, (untreated at 0.11 mg L^{-1}, glyphosate at 0.24 mg L^{-1}, 2,4-D at 0.77 mg L^{-1}, and imazamox at 0.55 mg L^{-1}). Open-water areas of the back-end sloughs had 2.20 mg L^{-1}.

In the back-end sloughs, the open-water mean dissolved oxygen was 3.91 mg L^{-1}, while in the channel-side open-water areas, it was much higher at 7.53 mg L^{-1}. The percentage of time below 5.0 mg L^{-1} in the open water of the back-end sloughs (Table 1) was 50.2% from 2 June to 16 June (pretreatment) and increased to 55.0% of the time from 17 June to 27 July (posttreatment). In the untreated plots, the percentage of time below 5.0 mg L^{-1} was 99.7% pretreatment, and decreased to 96.0% (a 3.7% decrease) in the posttreatment time, 17 June to 27 July. Each of the treatments showed a slightly larger decrease in time below 5.0 mg L^{-1}. The imazamox plots decreased 5.5% (92.0 to 86.9%), the glyphosate plots decreased 5.9% (87.1 to 81.9%), and the 2,4-D plots decreased 10.5% (89.7 to 80.4%).

When pretreatment and posttreatment mean dissolved oxygen was compared for each treatment in the back-end slough trial, there was no significant difference in dissolved oxygen levels for any of the treatments ($P > 0.9214$ for all comparisons). These results show that herbicide treatments did not decrease the availability of dissolved oxygen for fish, but the treatments also did not create new highly oxygenated habitat in the back-end sloughs. The dissolved oxygen remained so low in the back-end sloughs, even in the open water, that fish needing 5.0 mg L^{-1} of dissolved oxygen are unlikely to use these areas for habitat. None of the herbicide treatments caused the mean to increase above 5.0 mg L^{-1}. Each of the treatments in the back-end sloughs did have more time above 5.0 mg L^{-1} than the untreated plots, but for none of the treated areas was the level above 5.0 mg L^{-1} more than 20% of the total time. Treatment of these areas is recommended if they serve as a source population or create a hindrance to boating, but treating the waterhyacinth is unlikely to create fish habitat in the back-end sloughs.

In the long term, one of the goals of herbicide treatment in the Delta is the creation and maintenance of highly oxygenated open-water areas with dissolved oxygen near saturation levels. A concern in treating waterhyacinth with herbicides is that the dissolved oxygen under the treated area would temporarily decrease as the plants decay. Moving from pre- to posttreatment, the percentage of time below 5.0 mg L^{-1} in the untreated plots nearly doubled (from 15.5 to 30.3%), while in the treated plots, the time below 5.0 mg L^{-1} had a much smaller increase in the glyphosate plots (from 42.3 to 46.7%) and actually declined from 21.0 to 15.9% in the 2,4-D plots. Similarly, Tobias et al. (2019) reported that dissolved oxygen levels under waterhyacinth mats were below regional averages in the Delta prior to herbicide treatment, but increased to regional averages after treatment. They hypothesize that the twice-daily tidal movement may be the reason for the lack of a sharp decrease in dissolved oxygen following herbicide treatment.

In the channel-side trial, dissolved oxygen below 5.0 mg L^{-1} was recorded in all the plots during the period of the study, including the open-water plots, but the dissolved oxygen under the waterhyacinth canopies was below 5.0 mg L^{-1} for a greater proportion of the time. Other studies (Madsen 1997, Tobias et al. 2019, Toft 2000) also found that the water column below waterhyacinth canopies had low dissolved oxygen content. It is likely that fish would exhibit avoidance of these low-oxygen areas, as long as there were areas of the water body that were kept clear of waterhyacinth canopy. It is important for the maintenance of fish habitat and migration that waterhyacinth not be allowed to extend across the entire body of water. During June and July, when there is rapid waterhyacinth growth, the plots left untreated showed a decline of 0.82 mg L^{-1} in oxygen level, while the treated plots had a small increase (0.12 to 0.21 mg L^{-1}). The results of this study showed that treating channel-side populations of waterhyacinth with glyphosate and 2,4-D can be done without significantly decreasing dissolved oxygen levels and the removal of waterhyacinth from channel-side areas can create more highly oxygenated water for fish habitat and migration.

SOURCES OF MATERIALS

[1] PME miniDO$_2$T Logger, Precision Measurement Engineering, Inc., 1487 Poinsettia Ave., Vista, CA 92081.

[2] Roundup Custom®, EPA No. 524-343, Monsanto Co., 800 N. Lindberg Blvd., St. Louis, MO 63167.

[3] Weedar® 64, EPA No. 71368-1, Nufarm Inc., 11901 S. Austin Ave., Alsip, IL 60803.

[4] Clearcast®, EPA No.241-437-67690, SePRO Co., 11550 N. Meridian St., Ste. 600, Carmel, IN 46032.

[5] Agridex, Helena Agri-Enterprises, LLC, 225 Schilling Blvd., Collierville, TN 38017.

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