1   Reconciling fish and farms: Methods for managing California rice fields as salmon habitat

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14 Abstract

15   The rearing habitat for juvenile Chinook Salmon (Oncorhynchus tshawytscha) in

16 California, the southernmost portion of their range, has drastically declined throughout the past

17 century. Recently, through cooperative agreements with diverse stakeholders, winter-flooded

18 agricultural rice fields in California's Central Valley have emerged as promising habitat for

19 rearing juvenile Chinook Salmon. From 2013 to 2016, we conducted a series of experiments

20 examining methods for rearing fall-run Chinook Salmon on winter-flooded rice fields in the

21 Yolo Bypass, a modified floodplain of the Sacramento River in California. These included: 1)

22 influence of field substrate differences from previous season rice harvest; 2) effects of depth

23 refugia from avian predators (trenches); 3) field drainage methods to promote efficient egress of

24 fish; and 4) in-field salmon survivorship over time. Zooplankton (fish food) in the winter-flooded

25 rice fields were 53-150x more abundant when directly compared to the adjacent Sacramento

26 River. Correspondingly, somatic growth rates of juvenile hatchery-sourced fall-run Chinook

27 Salmon stocked in rice fields were two to five times greater versus fish in the adjacent

28 Sacramento River. Post-harvest field substrate treatments had little effect on the lower trophic

29 food web and had an insignificant effect on growth rates of in-field salmon. Though depth

30 refugia did not directly increase survival, it buffered maximum water temperatures in the

31 trenches and facilitated outmigration from fields during draining. Rapid field drainage methods

32 yielded the highest survival and were preferable to drawn-out drainage methods. High initial

33 mortality immediately after stocking was observed in the survival over time experiment with

34 stable and high survival after the first week. In-field survival ranged 7.4–61.6% and increased

35 over the course of the experiments. Despite coinciding with the most extreme drought in

36 California's recorded history, which elevated water temperatures and reduced the regional extent

37   of adjacent flooded habitats which concentrated avian predators, the adaptive research

38   framework enabled incremental improvements in design to increase survival. The abundance of

39   food resources and exceptionally high growth rates observed during these experiments illustrate

40   the benefits associated with reconciling off-season agricultural land use with fish conservation

41   practices. Without any detriment to flood control or agricultural yield, there is great promise for

42   reconciliation ecology between agricultural floodplains and endangered fish conservation where

43   minor alterations to farm management practices could greatly enhance the effectiveness of fish

44   conservation outcomes.

45

Introduction

47   Reconciliation ecology, or the modification of human dominated ecosystems for wildlife

48   conservation is becoming increasingly important, especially in freshwater ecosystems [1,2].

49   Indeed, streams, rivers and their associated floodplains are some of the most altered ecosystems

50   in the world, and reconciliation ecology will be increasingly needed to preserve endangered

51   species in degraded environments, and assist in recovering declining fauna [3–5]. Given human

52   population expansion and the concurrent growth of agriculture, multi-benefit land use

53   agreements are needed that align with the needs of societies as well as ecosystems [6].

54   Agricultural floodplains are an ideal location for case-studies on innovative arrangements since

55   they are managed to perform economically valuable functions of human food production and

56   flood risk mitigation as well as still providing passive benefits through the breakdown of organic

57   material, nutrient cycling, aquifer recharge, habitat creation, and conservation of biodiversity in

58   heavily altered landscapes [7,8]. Though river floodplain environments are largely in decline

59   globally [9,10], floodplain-oriented reconciliation ecology is especially attractive because

60   exposure of large numbers of fish to abundant food resources and habitats similar to those in

61   which native species are adapted may benefit survival and fitness [11,12]. The culturing of fish

62   in rice fields has successfully taken place for thousands of years in East Asia during both the

63   growing season and off-season, providing a valuable protein resource, natural fertilizer for

64   agricultural fields, and refugia/food for native fishes [13,14]. In North America, much of the

65   existing reconciliation work in agricultural floodplains has focused on waterfowl conservation

66   [15,16]; thus applications for fishes have lagged behind. Resultantly, there are myriad important

67   but fine-detailed questions regarding how to best prepare agricultural floodplains to enable fish

68   conservation.

69   *Oncorhynchus tshawytscha*, commonly known as Chinook Salmon, are declining in

70   California [17]. A conservative pre-European establishment population estimate in the Central

71   Valley fish was 2 million annual adult spawners, and sustained a sizable commercial ocean

72   fishery [18]. Anthropogenic causes of its decline are related to a combination of overfishing, dam

73   and levee construction, water diversions, land use changes, logging, hatcheries, and climate

74   change [19,20]. Current restoration efforts designed to improve spawning conditions and

75   produce more juvenile salmon include managing for minimum instream flows, cold water

76   releases, gravel enhancement, trap-and-haul programs, and hatchery production [21,22].

77   However, the ultimate success of these efforts, measured by resulting adult returns, depends

78   largely on freshwater rearing conditions and the correlated early ocean success of juveniles [23].

79   California's Central Valley floodplain is an optimal region for practicing floodplain

80   reconciliation ecology due to the amount of wetland habitat that has been lost in this region

81   through the past century. Prior to the mid-1800s, there were an estimated 4 million acres of

82   seasonal wetlands in California's Central Valley [24], which provided floodplain habitat with an

83   abundance of food resources juvenile Chinook Salmon. Of the historic wetland habitats in

84   California, approximately 95% of floodplain habitat has been disconnected from rivers by levees

85   and channelization, drastically reducing quality rearing conditions for out-migrating salmon

86   [25,26]. Much of the remaining wetland habitat accessible to juvenile salmon is highly altered,

87   confined to flood bypasses, and designed to drain flood waters rapidly to protect cities while

88   accommodating agricultural production in the dry season. Though much of the historical alluvial

89   floodplain in California is inaccessible to salmon with remaining areas confined to primarily

90   agricultural lands in the Yolo Bypass, Sutter Bypass, and other parcels located within Army

91   Corps river levee system, many properties of productive seasonal wetlands persist, presenting

92   opportunities for conservation. In particular, winter-flooded rice fields develop high densities of

93   invertebrate prey that promote fast juvenile Chinook Salmon growth rates in addition to

94   environmental conditions that resemble natural habitat conditions [27–30].

95   Using irrigation infrastructure to flood large areas within existing migratory routes during

96   the winter non-growing season presents a potential pathway to expanding the extent and

97   enhancing the quality of rearing habitat available to the salmon populations of the Central

98   Valley. Managed agricultural floodplains have the potential to supply juvenile fish with high

99   quality floodplain habitat and abundant natural food sources before downstream migration

100   [29,31]. These benefits accrue with prolonged duration of floodplain inundation with extended

101   flooding during the winter and early spring seasons allowing for the development of invertebrate

102   prey and improved foraging opportunities for fish [32]. Vigorous somatic growth of juvenile

103   salmon is typically observed in fish rearing under these floodplain conditions, leading to

104   potential survivorship benefits during outmigration [30,33]and their critical transition to the

105   ocean environment [34,35]. While the potential benefits to juvenile Chinook Salmon rearing in

106 flooded rice fields is well established, there is little research testing methodologies for

107 establishing the optimal physical and biological conditions to achieve maximal benefit in

108 managed agricultural floodplains.

109 The primary goal of this study was to compare potential farm management practices

110 intended to improve habitat conditions and growth and survival of juvenile Chinook Salmon

111 within winter-flooded post-harvest rice fields on the floodplain of the Central Valley of

112 California. Data on which methods provide the best conditions for juvenile salmon could be

113 useful to growers interested in participating in fish conservation activities and resource managers

114 developing guidance for multi-benefit land use intended to improve the habitat quality of

115 managed floodplains for salmon and other native fishes of conservation concern. Starting in

116 2013, we utilized an adaptive research framework to test rearing methodology of juvenile salmon

117 yearly until 2016. In 2013, our objective was to investigate food resources (invertebrate prey)

118 and salmon growth response to rice field substrate types (comparing post-harvest field

119 preparation methods). In 2014, we investigated the role that depth refugia played in determining

120 in-field survival and outmigration behavior. In 2015, water drainage practices were investigated

121 to determine if natural floodplain hydraulics could be mimicked to maximize efficient egress of

122 juveniles upon field draining. In 2016, we investigated in-field survival over time to evaluate

123 optimal rearing durations.

124

Methods

Study area

127 Experiments took place in the Yolo Bypass, a 24,000-ha flood bypass along the

128 Sacramento River in California, USA. Nine 0.81 ha replicated fields were constructed on Knaggs

129   Ranch—a farm predominantly producing rice (Fig 1). An inlet canal routing water from the

130   Knights Landing Ridgecut Canal independently fed each of the nine fields, and all fields drained

131   into an outlet canal. The outlet canal ultimately emptied into the Tule Canal, which runs north to

132   south along the east side of the bypass. Each field had rice boxes (structure using stacked boards

133   to control water elevation and flow) on the inlet and outlet of each field. Water depths, as

134   measured in the middle of the fields, were maintained between 0.3m to 0.5m for all years. Inlet

135   structures were fitted with 4mm mesh screens to permit water inflow and prevent egress of

136   stocked salmon. Outlet structures were fitted with mesh screens in the 2013 and 2016

137   experiments. However, in 2014 and 2015, outlet structures were left open with a 5-cm diameter

138   hole drilled in the middle of a 3.8cm × 14cm board and placed near the top of the water level in

139   the rice box to investigate volitional outmigration patterns of the stocked salmon. Each outlet

140   structure was fitted with a live car trap placed in the outlet canal, which allowed for collection of

141   all exiting fish. In 2014 and 2015, live cars were checked daily for the duration of the

142   experiments to enumerate the number of emigrating salmon. In past experiments we observed a

143   tendency for a portion of hatchery fish to "scatter" upon initial release into floodplain fields. This

144   behavior reliably abated after several days as fish acclimated to new conditions. For this reason,

145   downstream exiting fish were restocked back to the inlet side of the fields for the first week of

146   2014. In 2015, fish were similarly restocked for 2 weeks.

147

148   **Fig 1. Map of the study area.** Geographic extent of the Yolo Bypass of California (left) with a

149   detailed view of the nine experimental rice fields (right).

150

151   # Experiments

Substrate type – 2013

153   After harvest, rice farmers remove residual rice straw remaining in the fields using one of

154   several methods; thus an important question was whether differences in treatment of rice straw

155   created different outcomes for rearing fish. In 2013, nine fields were randomly assigned to one of

156   three post-harvest substrate treatments: rice stubble, disced, or fallow. The rice stubble substrate

157   treatment consisted of standing stalks (heights ranging from 0.23-0.35m) that remained after rice

158   plants were cut for harvest using a rice harvesting combine tractor. The disced treatment

159   consisted of plowing rice straw into the soil, a practice farmers use to promote stubble

160   decomposition. The fallow habitat had not been planted with rice during the previous growing

161   season but instead consisted of weedy herbaceous vegetation that voluntarily colonized the fields

162   during the growing season and was left standing during the experiment.

163   The 2013 experiment was described in detail by our colleagues [27] from the lower

164   trophic food web perspective and referenced in a forthcoming overview of research on salmon in

165   farm fields [36]. The methods are briefly summarized above to provide context for subsequent

166   years of the evolving project which was built on an adaptive research framework.

167

Depth refugia – 2014

169   Avian predation on fish in aquaculture fields is a well-known problem [37–39]. Avian

170   predation has potential to be a significant source of mortality on fish in winter-flooded rice fields

171   as California's Central Valley is positioned directly within the winter habitat of diverse bird

172   populations in the Pacific flyway [40,41]. We evaluated trenching as one method for reducing

173   potential avian predation on fish in winter-flooded rice fields. In 2014, nine fields all with a

174   disced substrate, were randomly assigned to one of three treatments: three fields were assigned

175   no perimeter trench, three were assigned a 0.5m deep perimeter trench, and three were assigned a

176   1.0m deep perimeter trench. All trenches were constructed on the north and east sides of the

177   fields running continuously from the inlet structure in the northwest corner to the drain structure

178   in the southeast corner. All trenches were approximately 1.0m wide with the outermost edges of

179   the trench spaced approximately 1.0m from the exterior levee surrounding the field. We created

180   this spacing specifically so depth refuges were outside the striking distance of wading birds such

181   as herons and egrets that frequent the shallow water of the perimeter levees. Survival data for 3

182   fields was excluded from the analysis due to loss of containment on the inlet side of three fields

183   (fields 3, 4, and 7, one from each treatment) during the last week of the experiment allowing fish

184   to escape upstream into the inlet canal. Ancillary effects of the trench treatments including field

185   drainage efficiency and volitional migration patterns were investigated between treatments.

186

Drainage practices – 2015

188   Floodplain hydrology provides important cues for movement and egress of floodplain

189   species [42,43]. Managing winter-flooded rice field habitat for fishes may require the

190   manipulation of draining hydrology to maximize survival and volitional egress of fish off fields.

191   These dynamics could be especially important in rice fields where intermittent floods could

192   entrain wild salmon and other species within fields (e.g., in the Yolo or Sutter Bypasses of the

193   California Central Valley). To investigate drainage practice effects on fish survival, the nine

194   fields were randomly assigned one of three draining treatments: 1) fast drain, where inlet water

195   was cut off and outlet boards were removed rapidly, resulting in the water draining off the fields

196   in a single day; 2) slow drain with inflow, where water levels were lowered by 5 cm per day at

197   the outlet while inflow was maintained through a mesh screen; and 3) slow drain without inflow,

198   where water levels were lowered 5 cm per day at the outlet and inflow was cut off by boarding

199   up the inlet structure. The drainage duration for slow drain procedures lasted for 10 days with

200   daily outmigration of salmon measured in the outlet traps. All nine experimental fields had a rice

201   stubble substrate following the rice harvest in fall 2014, and a 0.5m deep perimeter trench was

202   constructed in all fields connecting the inlet and outlet structures running along the north and

203   east sides of the fields. The trenches were approximately 1.0m wide and spaced 1.0m infield

204   from perimeter levees.

205

Survival over time – 2016

207   Because spatiotemporal variation in predation risk on fish and thermal-oxygen conditions

208   can be significant (especially in late winter and early spring), in-field survivorship of fish

209   remains a concern. During 2016, to examine in-field survivorship of juvenile salmon over time,

210   fish were stocked in six of the nine flooded experimental fields. During each of six weeks

211   following stocking, one randomly selected field was drained until the end of the 6-week

212   experiment. The fast drain procedure, as detailed in the 2015 experiment, was used in all fields.

213   All fields had fallow habitat due to lack of water allocation for the 2015 growing season during

214   an ongoing drought, and all fields had 0.5m deep trenches carried over from the previous 2015

215   experiment. An impending bypass flood event near the end of the study forced the drainage of

216   the last field 4 days earlier than scheduled.

217

In-field water temperature

219   Water temperature in shallow inundated fields could be a stressor to juvenile salmon

220   during warm weather periods with potential effects of slower growth, reduced smolting indices

221   and increased predation vulnerability [44]. Across all years and fields, we recorded continuous

222   water temperatures in 15-min intervals using HOBO U22 temperature loggers (Onset Computer

223   Corporation, Bourne, Massachusetts, USA) anchored in a fixed vertical position on a metal t-post

224   approximately 10cm above the substrate in the middle of each field as well as trench substrate

225   for a representative set of treatments when applicable.

226

Zooplankton abundance

228   Throughout all years, a randomly stratified subset of three fields was sampled for

229   zooplankton weekly except in 2013 where all nine field were sampled weekly. A 30-cm diameter

230   150-μm mesh zooplankton net (with the exception of the 2016 experiment, which used a 15-cm

231   diameter 150-μm mesh net) was thrown 5 m and towed through the water column four times,

232   once in each cardinal direction. In 2013, benthic macroinvertebrates were sampled separately

233   using benthic sweeps, but due to high sedimentation, high spatial and temporal sample

234   replication, and low overall contribution to the invertebrate community, the additional processing

235   was deemed unnecessary in subsequent years. Furthermore, the zooplankton tow method is

236   effective for assessing pelagic zooplankton and macroinvertebrate community assemblages while

237   improving sample processing efficiency since it avoids the heavy sedimentation associated with

238   benthic sweeps on wetland substrates [45]. Additionally, we also relied on the stomach contents

239   of in-field salmon to better inform the assemblage of macroinvertebrates present in the

240   floodplain food web and their contribution to the diet of in-field salmon (methods in next

241   section). Sampling locations were determined randomly within the test plots via a selection of

242   random x and y distances from a random number table. All samples were preserved in a solution

243   of 95% ethanol. Organisms were identified with the aid of a dissecting microscope at four times

244   magnification to the lowest taxonomic level possible using several widely recognized keys [46–

245   48]. Abundance estimates were calculated from homogenized subsamples of known volume and

246   extrapolated to the volume sampled during the initial net throws.

247

248   **Salmon stomach contents**

249   Stomach contents of sacrificed salmon captured during seining (2013–2015) and

250   sequential field draining (2016) were dissected for diet analysis. A total of 532 salmon stomachs

251   (2013: n = 268, 2014: n = 144, 2015: n = 90, 2016: n = 30) were dissected using a dissecting

252   microscope at four times magnification. Prey items were enumerated, but due to partial

253   decomposition, prey item identification in the stomachs was limited to taxonomic order.

254

255   **Overall salmon survival and growth**

256   Estimates of initially stocked salmon in each field were calculated by establishing a fish

257   per kilogram ratio and multiplying by the total weight applied to each field, except in 2016

258   where the overall number of stocked fish was sufficiently low to count individually (Table 1).

259   Fish lethally sampled for stomach content analysis during weekly sampling were subtracted from

260   the initial stocking estimate. Total salmon survival in each field was cumulatively enumerated in

261   the outlet live car traps except during the restocking phase of 2014 and 2015 when volitionally

262   emigrating fish were restocked to the inlet side of the fields. During field drainage, seines were

263   used to collect stranded fish out of standing water and these fish were added to the cumulative

264   survival count from the outlet live cars with the recovery method recorded. Survival in 2015 was

265   calculated from only the fast drain treatment fields since the drawn out drainage methods were

266   not comparable to drainage methods in other years.

267   Prior to stocking in each year, mean initial fork length and wet weight were calculated

268   from a random sample of 30 live fish measured to the nearest millimeter and weighed to the

269   nearest hundredth of a gram with an Ohaus Scout Pro SP202 scale (Table 1). For 2013–2015, we

270   conducted weekly in-field fish sampling with a seine to capture a target of 30 fish per treatment,

271   with the fork length and wet weight measured. In 2016, fish size data were collected from a

272   random sample of 30 fish in out-migrant traps as individual fields were drained weekly.

273

274   **Table 1. Summary of salmon stocking dates, experiment durations, stocking densities (fish**

275   **m^{-2}), mean initial fork length (mm), and mean initial wet weight (g).**

Year	Stocking date	Experiment duration (days)	Stocking density (fish m^{-2})	Mean initial fork length (mm)	Mean initial wet weight (g)
2013	Feb 19	37–41	0.57	53	1.53
2014	Feb 4	36–45	0.59	43	1.01
2015	Feb 5	22-32	0.49	50	1.37
2016	Feb 1	7–38	0.12	40	0.68

276

Statistical analysis

278   Percent survival for each field was calculated as the total recovered fish divided by initial

279   stocked fish times 100. Analysis of covariance (ANCOVA) was used to test for interaction

280   effects between field substrate treatment and time which would indicate treatment effects on

281   salmon growth rates. In this model, fork length was the dependent variable with field substrate,

282   day of the experiment and an interaction term as the independent variables. When the

283   assumptions of normality and homogeneity of variance were satisfied, as tested by the Shapiro-

284   Wilk and Levene tests respectively, a one-way analysis of variance (ANOVA) was used to test

285   for significant differences in survival due to field drainage treatments. A post hoc Tukey

286   honestly significant differences (HSD) test was used to test all pairwise comparisons of field

287   drainage practices. When the assumptions of normality and/or homogeneity of variance were not

288   satisfied, non-parametric Kruskal-Wallis analysis was used to test for significant differences in

289   survival and daily volitional outmigration due to field trench depth treatments. A post hoc

290   Dunn's test was used to test all pairwise comparisons of daily volitional outmigration due to field

291   trench depth treatments. Linear regression was used to estimate apparent growth rates and to

292   examine the relationship between salmon survival (dependent variable) and day of the

293   experiment (independent variable). Linear regression was also used to evaluate the relationship

294   between daily maximum water temperature differences in the trenches (dependent variable) and

295   daily maximum water temperature in the middle of the field (independent variable). Statistical

296   significance was declared at $\alpha < 0.05$ level. All analyses were conducted in R v3.6.1 (R Core

297   Team, 2019) [49].

298

Results

300

Substrate type – 2013

301   Apparent fork length growth rate for juvenile salmon did not differ significantly between

302   treatments (ANCOVA, $F = 2.16$, $df = 2$, $P = 0.11$). The slopes from individual linear regressions

303   of fork length predicted by day for each treatment resulted in estimated apparent growth rates of

304   1.01 mm d-1 for the stubble treatment, 0.99 mm d-1 for the disced treatment, and 0.95 mm d-1

305   for the fallow treatment.

306   Our colleagues [27] found no statistical difference between total abundance of

307   zooplankton between treatments, but did find high overall abundance and a trend of increasing

308 zooplankton over experiment duration. Additionally, our colleagues [27] found that across all

309 samples, cladocera were the most abundant group of zooplankton, making up over 50% of the

310 total zooplankton assemblage.

311 Cladoceran zooplankton was the most common prey item found in juvenile salmon

312 stomach contents as this taxon comprised on average 94.0% ± 1.0% SE of the diet composition

313 across all treatments. Chironomid midges (diptera) were the second most common prey item and

314 comprised an average of 4.8% ± 1.0% SE of the diets. Diet composition was slightly more

315 diverse in the fallow treatment with an average of 87.3% ± 2.6% SE percent of prey items

316 composed of cladocerans compared with an average of 97.4% ± 1.2% SE in the disced treatment

317 and 97.3% ± 1.0% SE in the stubble treatments. A chironomid midge hatch isolated in the

318 southernmost field (field 9) was responsible for the increased prey diversity resulting in diets

319 composed of an average of 69% cladocera and 30% diptera. The other two fallow replicates had

320 an average diet composition of 96% cladocera.

321

Depth refugia – 2014

323 Depth treatments did not have a significant effect on survival (Kruskal-Wallis, $\chi^2 = 0.86$,

324 df = 2, P = 0.65). Depth treatments had a significant effect on daily volitional emigration of fish

325 before draining (Kruskal-Wallis, $\chi^2 = 14.70$, df = 2, P < 0.001). A post-hoc Dunn's test revealed

326 that the two trenched treatments had significantly more daily volitional outmigration compared

327 to the no trench treatment (Dunn test, 0.5m trench – no trench: P < 0.001, 1m trench – no trench:

328 P = 0.003), but that the two trench treatments were not significantly different (0.5m trench – 1m

329 trench: P = 0.64). The average cumulative volitional outmigration before field drainage in the

330 two trenched treatments was 15.4% ± 5.3% SE compared to the trenchless treatment, which had

331   3.3% ± 1.2% SE, indicating the trenches may have functioned as a migratory pathway aiding in

332   volitional outmigration prior to field drainage. A relatively high rate of initial volitional

333   emigration was seen in the first week (1.5%) across all fields, followed by a much lower rate of

334   emigration in the second week (0.2%), and steadily increasing emigration in weeks three through

335   five (0.5%, 1.6%, 5.6% respectively). Manual fish recovery with a seine at the end of field

336   drainage in the trenchless fields ranged between 5 to 20% of the total surviving fish compared to

337   less than 0.5% of survivors from the trenched fields which indicated a more efficient drainage

338   procedure in trenched fields. These findings suggested functional equivalence between the 0.5m

339   and 1.0m trench treatments.

340

Drainage practices – 2015

342   Average salmon survival in each of the three treatments, fast drain, slow drain with flow,

343   and slow drain without inflow, was 43.5% ± 6.5% SE, 22.8% ± 3.0% SE, and 11.4% ± 3.1% SE

344   respectively (Fig 2). The differences between field drainage treatments were significant

345   (ANOVA, F = 13.15, df = 2, P = 0.01). A post hoc Tukey HSD analysis revealed that pairwise

346   comparisons of survival in the fast drain treatment were significantly higher than either slow

347   drain treatment (P = 0.04 and P = 0.01 for slow with flow and slow without flow treatments

348   respectively), but differences in survival between the two slow drain treatments were not

349   significantly different from each other (P = 0.25). Volitional outmigration patterns were similar

350   to 2014 with relatively high initial emigration in the first week (2.7%), low emigration in the

351   second week (0.2%), and high emigration in week three (3.8%).

352

353 **Fig 2. Survival response to drainage treatment.** Bars represent mean percent survival between

354 drainage treatments from the 2015 experiment. The error bars denote standard errors.

355

Survival over time – 2016

357   Across all draining durations, in-field survival of juvenile salmon averaged 61.6% ± 6.5

358 SD, with the final field survival being 8.0% lower than the first field drained 31 days earlier (Fig

359 3). The slope of a linear survival regression model predicted by day (range: 7–38 days) was -

360 0.24% per day with an intercept of 67.4%. Due to low sample size (n = 6) and inherent

361 variability in overall survival, the linear survival model had a low adjusted R^2 and non-

362 significant P-value (Regression, F = 1.05, df = 4, P = 0.36, R^2 = 0.01), however, the model

363 coefficients indicate a relatively low attrition rate (slope) after a substantial initial loss (intercept)

364 of approximately one third during the first week of the experiment.

365

366 **Fig 3. Survival over time.** Bars represent percent survival of stocked salmon over time in

367 sequentially drained fields from the 2016 experiment. The dotted line represents the mean

368 percent survival from all fields.

369

In-field water temperatures

371   Continuously logged water temperatures at the center of the fields during experiments

372 from all years ranged between 5.5°C and 23.5°C. Water temperatures exceeding 21°C, which can

373 negatively affect growth potential and predator avoidance [44], were experienced 1.6% of the

374 time. Trenches generated thermal refugia in the bottoms of the trenches with lower daily

375 maximum water temperatures compared to the middle of the fields by an average of 1.0 ± 0.22

376 SE °C and 1.8 ± 0.25 SE °C for the 0.5m and 1.0m trenches, respectively. There was a

377 significant correlation between maximum daily water temperature in the middle of the fields and

378 the difference between the maximum daily water temperature in the middle of the field and

379 bottom of the 0.5m and 1.0m deep trenches (0.5m trench: regression, F = 10.4, df = 1,23, P =

380 0.004; 1.0m trench: regression, F = 43.89, df = 1,31, P < 0.001). Over the observed range of

381 daily maximum water temperatures in 2014 and 2015 of 11.4 to 21.1 °C, the regression slopes

382 showed 0.26 °C and 0.60 °C temperature reductions in the trenches per degree increase in the

383 middle of the field for the 0.5m and the 1.0m trenches respectively.

384

Overall zooplankton

386   Measured zooplankton densities during the experiment ranged from a low of 14,961

387 organisms m^{-3} on Feb 1st, 2016 in field 2 (fallow substrate) to a high of 231,966 organisms m^{-3}

388 on Mar 20th, 2013 in field 6 (disced substrate). Overall mean annual zooplankton density was

389 consistent each year and ranged from a low of 75,045 in 2016 to a high of 107,039 in 2015.

390 Overall mean zooplankton densities between substrates across all years were 82,191 ± 8,697 SE,

391 81,283 ± 5,804 SE, and 93,585 ± 9,703 SE organisms m^{-3} for the disced, fallow, and stubble

392 substrates, respectively. When directly compared to the adjacent Sacramento River channel

393 habitat the managed agricultural fields had ≥ 150x zooplankton abundance in 2013 [27] and

394 approximately 53x zooplankton abundance in 2016 [50].

395

396 **Table 2. Mean in-field zooplankton density m^{-3}, percent cladocera from in-field**

397 **zooplankton samples, and percent cladocera in salmon diets.**

Year	Mean total zooplankton density (m⁻³)	Mean percent cladocera in fields	Mean percent cladocera in diets (%)
2013	81,417	56.0%	94.0%
2014	96,768	52.9%	95.0%
2015	107,039	25.2%	92.5%
2016	75,045	16.4%	91.2%

398

Overall salmon stomach contents

400   Salmon consistently showed a preference for cladoceran zooplankton as this taxon

401 comprised >90% of the stomach contents in all years compared with ambient, in-field cladocera

402 percent composition ranging 16.4-56.0% (Table 2, Fig 4). Mean prey organism abundance in the

403 stomach contents for each year ranged from 158.3 ± 36.0 SE in 2016 to 278.9 ± 27.6 SE in 2013

404 indicating that invertebrate food resources were abundant in all years (Fig 4).

405

406 **Fig 4. Salmon growth, stomach contents, zooplankton resources, and water temperatures in**

407 **winter-flooded rice fields.** Plot rows from top to bottom: mean fork length (mm) with standard

408 deviation bars and linear regression line, mean prey organism abundance in salmon stomach

409 contents, mean density of in-field zooplankton (organisms m⁻³), and water temperature (°C) in

410 the middle of a representative field (field 4) for each year 2013-2016 in columns displayed from

411 left to right.

412

Overall salmon survival and growth

414   Survival between years was variable, ranging from 7.4% in 2013 to 61.6% in 2016 and

415   increased over the course of the multi-year experiment (Table 3). A significant increase in

416   survival was observed after 2013 when an undersized culvert in the drainage canal was replaced

417   allowing for much more rapid field draw down in subsequent years.

418   Juvenile Chinook Salmon apparent growth rates observed in experimental fields were

419   high in all years ranging from 0.81 mm d-1 and 0.12 g d-1 in 2015 to 1.28 mm d-1 and 0.21 g d-

420   1 in 2016 (Table 3). These growth rates were 2-5x higher than previously or concurrently

421   observed in the adjacent Sacramento River [50,51].

422

423   **Table 3: Mean percent survival, apparent fork length growth rate and apparent weight**

424   **growth rate for each year of the experiment.**

Year	Mean survival	Fork length growth rate (mm d^{-1})	Weight growth rate (g d^{-1})
2013	7.4%	0.99	0.19
2014	44.6%	0.99	0.14
2015	43.5%	0.81	0.12
2016	61.6%	1.28	0.21

425

Discussion

427   Rearing of juvenile Chinook Salmon within winter-flooded rice fields shows strong

428   potential for reconciling agricultural floodplain land use with habitat needs of an imperiled and

429   economically important fish. Winter-flooded rice fields demonstrated high production of

430   naturally occurring fish food (zooplankton) leading to high growth rates of salmon reared in

431   these environments. As with past fish conservation studies in altered environments [52–54], our

432   adaptive research approach enabled us to successfully answer experimental questions despite

433   unpredictable winter hydrologic and temperature regimes in the Central Valley.

434   In our studies, field substrate did not have a statistically significant effect on the

435   composition or abundance of zooplankton species. Similarly, no significant differences in growth

436   rates of rearing juvenile salmon were detected between post-harvest substrate treatments.

437   Overall, growth across all treatments was extremely fast and much greater than that documented

438   in the Sacramento River channel environments [29]. Accordingly, we do not recommend a

439   specific post-harvest straw management practice. Instead we feel that field preparation should be

440   left to the farmer. We do however, encourage future research that explores other approaches for

441   enhancing in-field habitats to decrease predation risk for rearing fish.

442   There is currently limited scope for providing avian predation refugia for fish inside of

443   winter-flooded rice fields. We investigated the potential of in-field trenches to provide depth

444   refuge from avian predation, but direct benefits to survival were found to be insignificant in this

445   study. Despite this result, we determined that trenches produced other beneficial by-products.

446   For example, the fields containing perimeter trenches connecting the inlet and outlet structures

447   showed higher rates of volitional emigration of salmon. We speculate that fish used the trenches

448   as migration corridors when emigrating from the fields resulting in a diversification of

449   emigration timing which has been identified as a key component of population stability via the

450   portfolio effect (Carlson and Satterthwaite, 2011) [55]. Additionally, the trenches buffered water

451   temperatures from the daily maximums observed in the middle of the fields and enhanced field

452   drainage with reduced standing water and stranding of fish during field drainage.

453   In floodplain river ecosystems, fishes often respond strongly to hydrological dynamics of

454   ascending and descending flood conditions [56–58]. Juvenile Chinook Salmon in the Central

455   Valley have evolved physiological and behavioral strategies for the use and egress from winter-

456   flooded floodplain habitats [28,33,59]. Accordingly, the dynamics of draining rice fields

457   containing juvenile Chinook Salmon may matter in terms of providing the appropriate type and

458   quantity of cues to promote the volitional egress of fish from fields with minimal stranding. In

459   our study, extending the drainage period and manipulating inflow conditions had a detrimental

460   effect on survival and the best method was a fast drain where fields were drained in a single day.

461   This was likely the result of increased vulnerability to predation and reduced thermal buffering

462   due to a prolonged period with shallower water depths. Again, these results provide a relatively

463   simple management recommendation for farmers in that a more complicated long drain does not

464   currently appear to be necessary. Rather, simple opening of water control structures combined

465   with volitional passage appears to be the best method. We encourage exploration of other

466   drainage methods, and production of other species in winter-flooded rice fields may require

467   different draining practices.

468   An initial mortality of approximately 33% was observed in the first week of the 2016

469   salmon survival over time experiment. The cause of this initial mortality is unknown but was

470   likely a combination of factors, including a stressful transport. Transport is a known stressor on

471   many fishes, including juvenile Chinook Salmon [60,61]. In our study, fish were captured from

472   hatchery raceways, coded wire tagged, allowed to recover for several days and then placed in a

473   fish hauling tank at high densities (up to 25,000 fish m^{-3}) and delivered to the fields in early

474   February. Exposing naïve hatchery salmon to a new environment in the flooded agricultural

475   fields may have increased stress as it necessitated behavioral adaptations of prey switching and

476   predator avoidance as well as rapid acclimation to the new physical water quality parameters.

477   After the startlingly high rate of initial mortality, survival stabilized in week 2 and remained high

478   for the remainder of the experiment. Without accurate assessment and accounting of initial post-

479   release mortality there is potential for fishery managers to be chronically overestimating habitat-

480   specific mortality rates determined by recapture of hatchery fish transported and released into

481   natural habitats. We therefore recommend that future research examine effects on initial post-

482   release mortality of transporting, acclimatizing, and releasing hatchery fish into the wild.

483   There has been a perceived conflict between conservationists and farmers when

484   managing off-season agricultural fields as fish habitats. While farmers have incentives to prepare

485   their fields for a new rice crop as early in the spring as possible, fish conservationists prefer to

486   keep the rice fields wet as late as possible to maximize fish growth and survival before release

487   into the river [32,33]. However, in practice, when weather conditions are good for fish (i.e., wet

488   and cool) in the late winter and early spring, they are generally not conducive to agricultural field

489   preparation. The inverse is also true, when spring conditions are dry and hot and generally

490   suitable for agricultural field preparation, water quality conditions (especially water temperature)

491   are often unsuitable for juvenile Chinook Salmon [62,63]. Thus, given proper timing and

492   coordination within an adaptive management framework, rice farmers and fish conservationists

493   can collaborate to promote threatened fisheries without impacting crop yields [29]. We therefore

494   encourage the continued development of frameworks that work for both fish and farms in

495   floodplain habitats in the Central Valley. In particular, incentive programs for farmers (e.g.,

496   through the USDA NRCS program) may be needed to promote these activities to their fullest

497   potential.

498   Land manager and farmer involvement has generally exceeded expectations in our

499   projects, and we are optimistic about continued stakeholder involvement for several reasons.

500   Given issues with water scarcity in the Central Valley [64,65], the dual-use of rice fields for

501   agriculture and rearing juvenile salmon could establish stronger water security for farmers [66].

502   Additionally, the reconciling of fish conservation and rice agriculture provides a sustainable

503   method for conducting a service of rice straw decomposition while using natural processes to

504   fuel a productive aquatic food web [27,67]. Salmon reared in the flooded rice fields exhibit

505   among the highest growth rates documented in freshwater in California (Fig 5) [29]. By creating

506   high quality habitat on their fields, farmers can help bolster fish populations by turning small fry

507   into large, healthy smolts rapidly during mid-winter when water temperatures are low, river

508   flows are high and when predators are less active, thus improving salmon survival rates during

509   outmigration [68].

510

511   **Fig 5. Weekly salmon growth images.** Standardized images of a representative juvenile

512   Chinook Salmon sampled weekly during the 2016 experiment.

513

514   We support current state and federal programs targeting the modification of existing

515   levee and weir infrastructure to allow fish in river channels to more frequently access managed

516   floodplain habitats during outmigration. We also see the need for additional science to track fish

517   after they leave the fields in order to evaluate the full lifecycle benefits to salmon having reared

518   on inundated agricultural fields (e.g., out-migration survival, smolt-to-adult return rates, and

519   physiological benefits). The exceptional productivity and resulting rapid rates of salmon growth

520   documented on the managed agricultural floodplain highlight the potential value of this habitat

521   for native fish conservation. Managed agricultural floodplains should not be thought of as a

522   replacing the need for preserving the last remnants of natural floodplains, nor should they

523   diminish the conservation need for restoring naturally functioning floodplains where feasible.

524 Managed agricultural floodplains are likely to become an important means for fishery managers

525 to produce ecologically functioning off-channel habits for imperiled native fish especially during

526 times of low water when remaining natural floodplain habitats do not inundate and are therefore

527 inaccessible to salmon populations confined to leveed stream channels.

528

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543

544 References

545 1.   Rosenzweig ML. Win-win Ecology: How the Earth's Species Can Survive in the Midst of

546   Human Enterprise. Oxford: Oxford University Press; 2003.

547   2.   Robertson GP, Swinton SM. Reconciling agricultural productivity and environmental

548   integrity: a grand challenge for agriculture. Frontiers in Ecology and the Environment.

549   2005;3: 38–46. doi:10.1890/1540-9295(2005)003%5B0038:RAPAEI%5D2.0.CO;2

550   3.   He F, Zarfl C, Bremerich V, David JNW, Hogan Z, Kalinkat G, et al. The global decline

551   of freshwater megafauna. Global Change Biology. 2019;25: 3883–3892.

552   doi:10.1111/gcb.14753

553   4.   Moyle PB. Novel Aquatic Ecosystems: The new reality for streams in california and other

554   mediterranean climate regions. River Research and Applications. 2013;30: 1335–1344.

555   doi:10.1002/rra.2709

556   5.   Strayer DL, Dudgeon D. Freshwater biodiversity conservation: recent progress and future

557   challenges. Journal of the North American Benthological Society. 2010;29: 344–358.

558   doi:10.1899/08-171.1

559   6.   Sal AG, García AG. A comprehensive assessment of multifunctional agricultural land-use

560   systems in Spain using a multi-dimensional evaluative model. Agriculture, ecosystems &

561   environment. 2007;120: 82–91.

562   7.   Cook HF. Floodplain agricultural systems: functionality, heritage and conservation.

563   Journal of flood risk management. 2010;3: 192–200. doi:10.1111/j.1753-

564   318X.2010.01069.x

565   8.   Davis AM, Moore AR. Conservation potential of artificial water bodies for fish

566   communities on a heavily modified agricultural floodplain. Aquatic Conservation: marine

567   and freshwater ecosystems. 2016;26: 1184–1196.

568   9.   Aarts BGW, Van Den Brink FWB, Nienhuis PH. Habitat loss as the main cause of the

569   slow recovery of fish faunas of regulated large rivers in Europe: the transversal floodplain

570   gradient. River Research and Applications. 2004;20: 3–23. doi:10.1002/rra.720

571 10. Tockner K, Stanford JA. Riverine flood plains: present state and future trends.

572   Environmental Conservation. 2002;29: 308–330. doi:10.1017/S037689290200022X

573 11. King AJ, Tonkin Z, Mahoney J. Environmental flow enhances native fish spawning and

574   recruitment in the Murray River, Australia. River Research and Applications. 2009;25:

575   1205–1218. doi:10.1002/rra.1209

576 12. Limm MP, Marchetti MP. Juvenile Chinook salmon (Oncorhynchus tshawytscha) growth

577   in off-channel and main-channel habitats on the Sacramento River, CA using otolith

578   increment widths. Environmental Biology of Fishes. 2009;85: 141–151.

579   doi:10.1007/s10641-009-9473-8

580 13. Fernando CH. Rice field ecology and fish culture - an overview. Hydrobiologia.

581   1993;259: 91–113. doi:10.1007/BF00008375

582 14. MacKay KT. Rice-fish culture in China. Ottawa: International Development Research

583   Centre; 1995.

584 15. Elphick CS, Taft O. Management of Rice Fields for Birds during the Non-Growing

585   Season. Waterbirds. 2010;33: 113–181. doi:10.1675/063.033.s114

586 16. Firth AG, Baker BH, Brooks JP, Smith R, Iglay RB, Davis JB. Low external input

587   sustainable agriculture_ Winter flooding in rice fields increases bird use, fecal matter and

588   soil health, reducing fertilizer requirements. Agriculture, Ecosystems {\&} Environment.

589   2020;300: 106962. doi:10.1016/j.agee.2020.106962

590 17. Katz J, Moyle PB, Quiñones RM, Israel J, Purdy S. Impending extinction of salmon,

591   steelhead, and trout (Salmonidae) in California. Environmental Biology of Fishes.

592   2012;96: 1169–1186. doi:10.1007/s10641-012-9974-8

593 18. Yoshiyama RM, Fisher FW, Moyle PB. Historical abundance and decline of chinook

594   salmon in the Central Valley region of California. North American Journal of Fisheries

595   Management. 1998;18: 487–521. doi:10.1577/1548-

596   8675(1998)018<0487:HAADOC>2.0.CO;2

597 19. Gregory S V, Bisson PA. Degradation and Loss of Anadromous Salmonid Habitat in the

598   Pacific Northwest. In: Stouder D.J., Bisson P.A., Naiman R.J. (eds) Pacific Salmon &

599   their Ecosystems. Pacific salmon their ecosystems. Boston, MA: Springer; 1994. pp. 277–

600   314. doi:10.1007/978-1-4615-6375-4_17

601 20. Jager HI, Rose KA. Designing Optimal Flow Patterns for Fall Chinook Salmon in a

602   Central Valley, California, River. North American Journal of Fisheries Management.

603   2003;23: 1–21. doi:10.1577/1548-8675(2003)023<0001:DOFPFF>2.0.CO;2

604 21. Merz JE, Setka JD. Evaluation of a Spawning Habitat Enhancement Site for Chinook

605   Salmon in a Regulated California River. North American Journal of Fisheries

606   Management. 2004;24: 397–407. doi:10.1577/M03-038.1

607 22. Phillips JL, Ory J, Talbot A. Anadromous Salmonid Recovery in the Umatilla Rwer

608   Basin, Oregon: a Case Study. JAWRA Journal of the American Water Resources

609   Association. 2000;36: 1287–1308. doi:10.1111/j.1752-1688.2000.tb05727.x

610 23. Unwin MJ. Fry-to-adult survival of natural and hatchery-produced chinook salmon

611   (Oncorhynchus tshawytscha) from a common origin. Canadian Journal of Fisheries and

612   Aquatic Sciences. 1997;54: 1246–1254. doi:10.1139/f97-032

613 24. Fretwell JD, Williams JS, Redman PJ. National water summary on wetland resources.

614   Vol. 2425. US Government Printing Office; 1996.

615   25.   Hanak E, Lund J, Dinar A, Gray B, Howitt R, Mount J, et al. Managing California's

616   water: from conflict to reconciliation. Public Policy Inst Calif, San Francisco; 2011.

617   26.   Whipple A, Grossinger RM, Rankin D, Stanford B, Askevold R. Sacramento-San Joaquin

618   Delta historical ecology investigation: exploring pattern and process. SFEI: Richmond;

619   2020 May.

620   27.   Corline NJ, Sommer T, Jeffres CA, Katz J. Zooplankton ecology and trophic resources for

621   rearing native fish on an agricultural floodplain in the Yolo Bypass California, USA.

622   Wetlands Ecology and Management. 2017; 1–13. doi:10.1007/s11273-017-9534-2

623   28.   Jeffres CA, Opperman JJ, Moyle PB. Ephemeral floodplain habitats provide best growth

624   conditions for juvenile Chinook salmon in a California river. Environmental Biology of

625   Fishes. 2008;83: 449–458. doi:10.1007/s10641-008-9367-1

626   29.   Katz JVE, Jeffres C, Conrad JL, Sommer TR, Martinez J, Brumbaugh S, et al. Floodplain

627   farm fields provide novel rearing habitat for Chinook salmon. PLoS ONE. 2017;12:

628   e0177409--16. doi:10.1371/journal.pone.0177409

629   30.   Sommer T, Harrell B, Nobriga M, Brown R, Moyle P, Kimmerer W, et al. California's

630   Yolo Bypass: Evidence that flood control Can Be compatible with fisheries, wetlands,

631   wildlife, and agriculture. Fisheries. 2001;26: 6–16. doi:10.1577/1548-

632   8446(2001)026<0006:CYB>2.0.CO;2

633   31.   Metcalfe NB, Valdimarsson SK, Morgan IJ. The relative roles of domestication, rearing

634   environment, prior residence and body size in deciding territorial contests between

635   hatchery and wild juvenile salmon. Journal of Applied Ecology. 2003;40: 535–544.

636   doi:10.1046/j.1365-2664.2003.00815.x

637   32.   Goertler PAL, Sommer TR, Satterthwaite WH, Schreier BM. Seasonal floodplain-tidal

638   slough complex supports size variation for juvenile Chinook salmon (Oncorhynchus

639   tshawytscha). Ecology of Freshwater Fish. 2017;27: 580–593. doi:10.1111/eff.12372

640   33.   Takata L, Sommer TR, Conrad JL, Schreier BM. Rearing and migration of juvenile

641   Chinook salmon (Oncorhynchus tshawytscha) in a large river floodplain. Environmental

642   Biology of Fishes. 2017;100: 1105–1120. doi:10.1007/s10641-017-0631-0

643   34.   Satterthwaite WH, Hayes SA, Merz JE, Sogard SM, Frechette DM, Mangel M. State-

644   Dependent Migration Timing and Use of Multiple Habitat Types in Anadromous

645   Salmonids. Transactions of the American Fisheries Society. 2012;141: 781–794.

646   doi:10.1080/00028487.2012.675912

647   35.   Woodson LE, Wells BK, Weber PK, MacFarlane RB, Whitman GE, Johnson RC. Size,

648   growth, and origin-dependent mortality of juvenile Chinook salmon Oncorhynchus

649   tshawytscha during early ocean residence. Marine Ecology Progress Series. 2013;487:

650   163–175. doi:10.3354/meps10353

651   36.   Sommer, T; Schreier, B; Conrad, J.L.; Takata, L; Serup, B; Titus, R; Jeffres, C; Holmes,

652   E; Katz J. Farm to Fish: Lessons from a Multi-Year Study on Agricultural Floodplain

653   Habitat. San Francisco Estuary and Watershed Science. 2020;Forthcomin.

654   37.   Glahn JF, Rasmussen ES, Tomsa T, Preusser KL. Distribution and relative impact of

655   avian predators at aquaculture facilities in the northeastern United States. North American

656   Journal of Aquaculture. 2011. doi:10.1577/1548-

657   8454(1999)061%3C0340:DARIOA%3E2.0.CO;2

658   38.   Mott DF, Waterbirds FLBC, 1995. A review of techniques for preventing cormorant

659   depredations at aquaculture facilities in the southeastern United States. The Journal of

660   Wildlife Management. 1995;18: 176. doi:10.2307/1521538

661   39.   Price IM, Waterbirds JGNC, 1995. Aquaculture and birds: the context for controversy.

662   The Journal of Wildlife Management. 1995;18: 33. doi:10.2307/1521522

663   40.   Elphick CS. Landscape Effects on Waterbird Densities in California Rice Fields:

664   Taxonomic Differences, Scale-Dependence, and Conservation Implications. Waterbirds.

665   2008;31: 62–69. doi:10.1675/1524-4695(2008)31[62:LEOWDI]2.0.CO;2

666   41.   van Groenigen JW, Burns EG, Eadie JM, Horwath WR, van Kessel C. Effects of foraging

667   waterfowl in winter flooded rice fields on weed stress and residue decomposition.

668   Agriculture, Ecosystems & Environment. 2003;95: 289–296. doi:10.1016/S0167-

669   8809(02)00097-X

670   42.   Arthington AH, Balcombe SR. Extreme flow variability and the boom and bust ecology of

671   fish in arid-zone floodplain rivers: a case history with implications for environmental

672   flows, conservation and management. Ecohydrology. 2011;4: 708–720.

673   doi:10.1002/eco.221

674   43.   Röpke CP, Amadio S, Zuanon J, Ferreira EJG, de Deus CP, Pires THS, et al.

675   Simultaneous abrupt shifts in hydrology and fish assemblage structure in a floodplain lake

676   in the central Amazon. Nature Publishing Group. 2016; 1–10. doi:10.1038/srep40170

677   44.   Marine KR, Cech Jr JJ. Effects of High Water Temperature on Growth, Smoltification,

678   and Predator Avoidance in Juvenile Sacramento RiverChinook Salmon. North American

679   Journal of Fisheries Management. 2004;24: 198–210. doi:10.1577/M02-142

680   45.   Cheal F, Davis JA, Growns JE, Bradley JS, Whittles FH. The influence of sampling

681   method on the classification of wetland macroinvertebrate communities. Hydrobiologia.

682   1993;257: 47–56. doi:10.1007/bf00013996

683   46.   Merritt RW, Cummins KW. An Introduction to the Aquatic Insects of North America. 4th

684   ed. Kendall Hunt Publishing; 1996.

685   47.   Thorp JH, Covich AP. Ecology and classification of North American freshwater

686   invertebrates. Academic press; 2009.

687   48.   Karanovic I. Recent freshwater ostracods of the world: Crustacea, Ostracoda, Podocopida.

688   Springer; 2012.

689   49.   R Core Team. R: A language and environment for statistical computing. Vienna, Austria:

690   R Foundation for Statistical Computing; 2019.

691   50.   Jeffres C, Holmes EJ, Sommer TR, Katz JVE. Detrital Food Web Drives Aquatic

692   Ecosystem Productivity in a Seasonally Inundated Managed Floodplain. BioRxiv. 2019;

693   610055.

694   51.   Sommer TR, Nobriga ML, Harrell WC, Batham W, Kimmerer WJ. Floodplain rearing of

695   juvenile Chinook salmon: evidence of enhanced growth and survival. Canadian Journal of

696   Fisheries and Aquatic Sciences. 2001;58: 325–333. doi:10.1139/cjfas-2019-0171

697   52.   Hutson AM, Toya LA, Tave D. Determining preferred spawning habitat of the endangered

698   Rio Grande silvery minnow by hydrological manipulation of a conservation aquaculture

699   facility and the implications for management. Ecohydrology. 2018;11: e1964--12.

700   doi:10.1002/eco.1964

701   53.   Johnson EL, Kozfkay CC, Powell JH, Peterson MP, Baker DJ, Heindel JA, et al.

702   Evaluating Artificial Propagation Release Strategies for Recovering Endangered Snake

703   River Sockeye Salmon. North American Journal of Aquaculture. 2020; naaq.10148--31.

704   doi:10.1002/naaq.10148

705   54.   Tave D, Toya LA, Hutson AM. Raising Fish in a Purpose-Built Conservation Aquaculture

706   Facility Using Conservation Aquaculture Management. North American Journal of

707   Aquaculture. 2019;81: 326–332. doi:10.1002/naaq.10097

708 55. Carlson SM, Satterthwaite WH. Weakened portfolio effect in a collapsed salmon

709   population complex. Canadian Journal of Fisheries and Aquatic Sciences. 2011;68: 1579–

710   1589. doi:10.1139/f2011-084

711 56. Balcombe SR, Arthington AH. Temporal changes in fish abundance in response to

712   hydrological variability in a dryland floodplain river. Marine and Freshwater Research.

713   2009;60: 146–159. doi:10.1071/MF08118

714 57. Castello L. Lateral migration of Arapaima gigas in floodplains of the Amazon. Ecology of

715   Freshwater Fish. 2008;17: 38–46. doi:10.1111/j.1600-0633.2007.00255.x

716 58. de Magalhães Lopes J, Alves CBM, Peressin A, Pompeu PS. Influence of rainfall,

717   hydrological fluctuations, and lunar phase on spawning migration timing of the

718   Neotropical fish Prochilodus costatus. Hydrobiologia. 2018;818: 145–161.

719   doi:10.1007/s10750-018-3601-4

720 59. Sommer TR, Harrell WC, Nobriga ML. Habitat Use and Stranding Risk of Juvenile

721   Chinook Salmon on a Seasonal Floodplain. North American Journal of Fisheries

722   Management. 2005;25: 1493–1504. doi:10.1577/M04-208.1

723 60. Maule AG, Tripp RA, Kaattari SL, Schreck CB. Stress alters immune function and disease

724   resistance in chinook salmon (Oncorhynchus tshawytscha). The Journal of endocrinology.

725   1989;120: 135–142. doi:10.1677/joe.0.1200135

726 61. Maule AG, Schreck CB, Bradford CS, Barton BA. Physiological effects of collecting and

727   transporting emigrating juvenile chinook salmon past dams on the Columbia River.

728   Transactions of the American Fisheries Society. 2011. doi:10.1577/1548-

729   8659(1988)117%3C0245:PEOCAT%3E2.3.CO;2

730   62.   Herbold B, Carlson SM, Henery R, Johnson RC, Mantua N, McClure M, et al. Managing

731   for salmon resilience in California's variable and changing climate. San Francisco Estuary

732   and Watershed Science. 2018;16. doi:10.15447/sfews.2018v16iss2art3

733   63.   Michel CJ, Ammann AJ, Lindley ST, Sandstrom PT, Chapman ED, Thomas MJ, et al.

734   Chinook salmon outmigration survival in wet and dry years in California's Sacramento

735   River. Canadian Journal of Fisheries and Aquatic Sciences. 2015;72: 1749–1759.

736   64.   Li R, Ou G, Pun M, Larson L. Evaluation of Groundwater Resources in Response to

737   Agricultural Management Scenarios in the Central Valley, California. Journal of Water

738   Resources Planning and Management. 2018;144: 4018078–4018079.

739   doi:10.1061/(ASCE)WR.1943-5452.0001014

740   65.   Ojha C, Shirzaei M, Werth S, Argus DF, Farr TG. Sustained Groundwater Loss in

741   California's Central Valley Exacerbated by Intense Drought Periods. Water Resources

742   Research. 2018;54: 4449–4460. doi:10.1029/2017WR022250

743   66.   Garnache C. Fish, Farmers, and Floods: Coordinating Institutions to Optimize the

744   Provision of Ecosystem Services. Journal of the Association of Environmental and

745   Resource Economics. 2015;2: 367–399. doi:10.1086/682167

746   67.   Devêvre OC, Horwáth WR. Decomposition of rice straw and microbial carbon use

747   efficiency under different soil temperatures and moistures. Soil Biology and Biochemistry.

748   2000;32: 1773–1785. doi:10.1016/S0038-0717(00)00096-1

749   68.   Nobriga ML, Feyrer F. Shallow-water piscivore-prey dynamics in California's

750   Sacramento–San Joaquin Delta. San Francisco Estuary and Watershed Science. 2007;5.
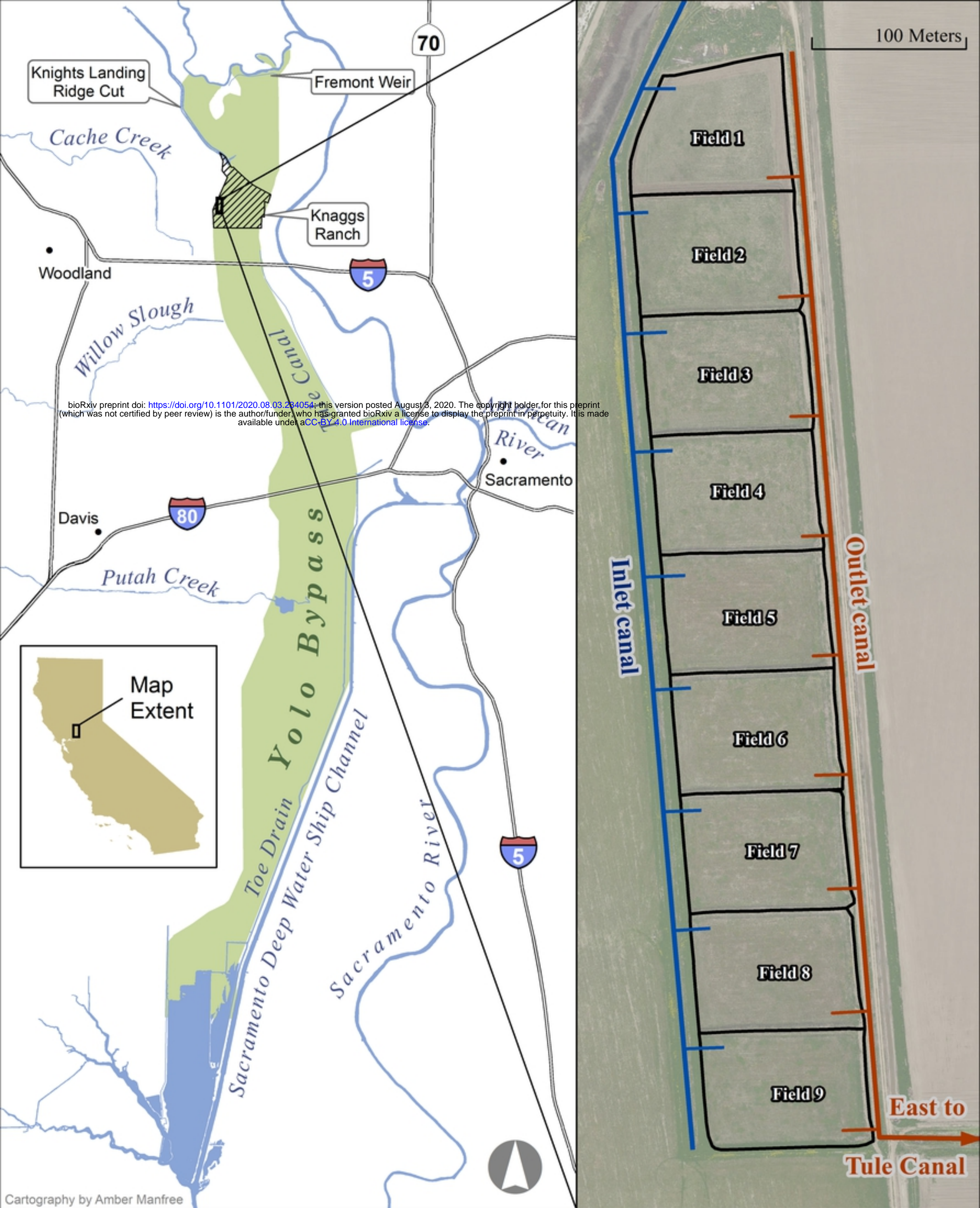
751   doi:10.15447/sfews.2007v5iss2art4
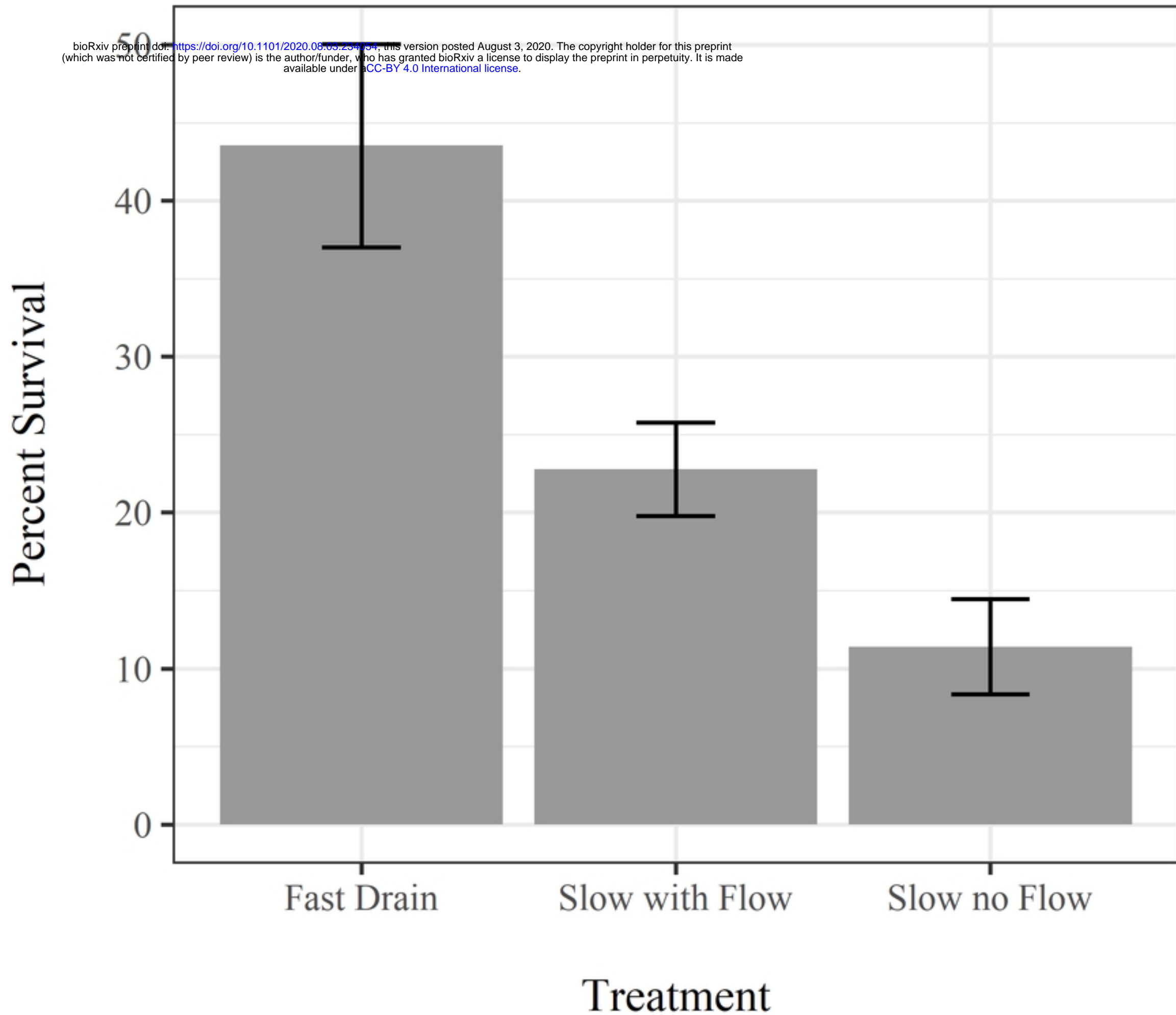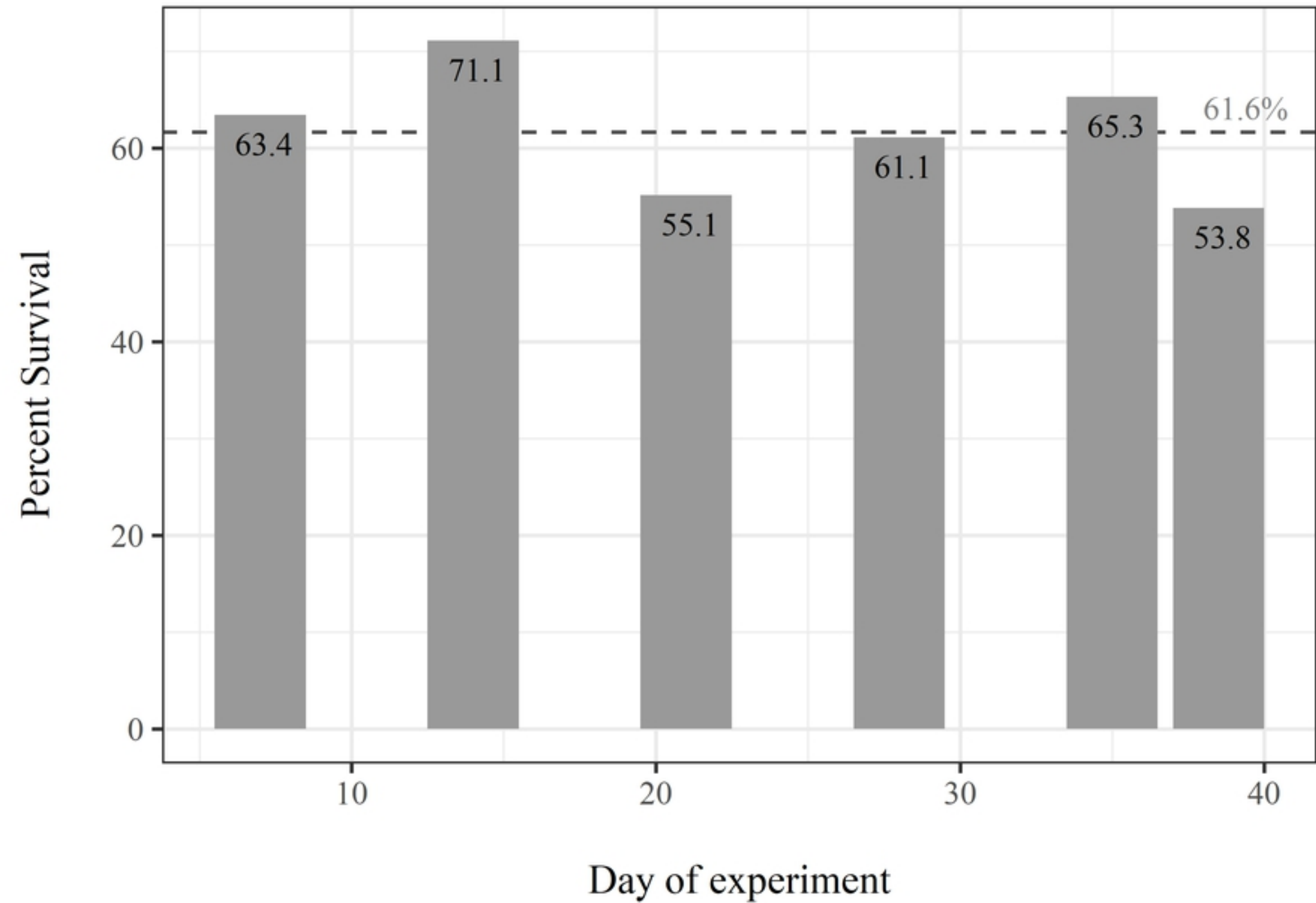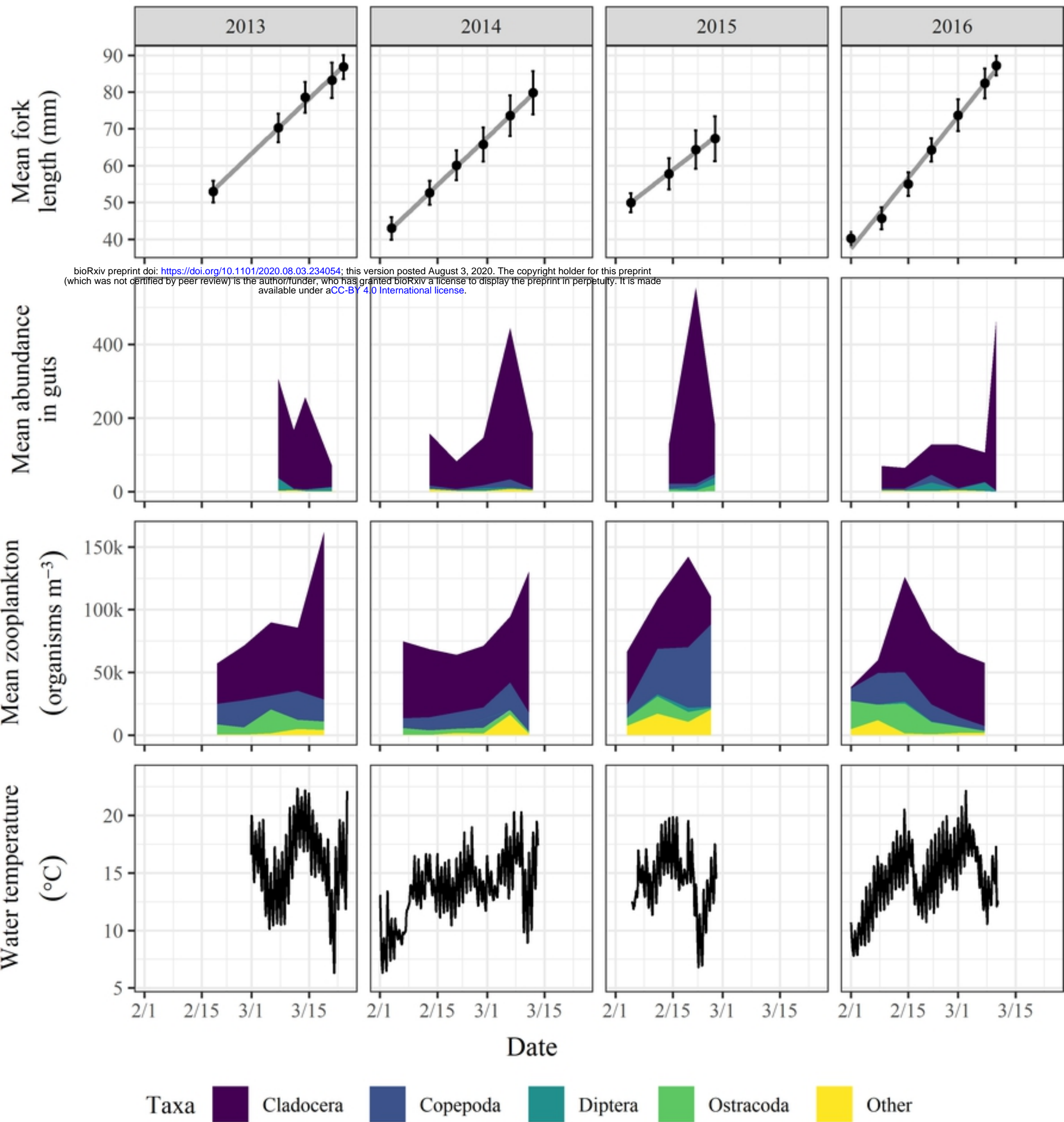
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Figure 1

Figure 2

Figure 3

Figure 4

Figure 5