**Supporting Information for:**

Hydrology-mediated ecological function of a large wetland threatened by an invasive predator

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**Appendix S1:**

*Analyses using catch-per-unit-effort (CPUE) of large predatory fishes and use of Shark River Slough and Water Conservation Area 3A as reference regions*

As an alternative to the presence/absence analyses used to assess the effects of swamp eels in the main text, we performed analyses that assessed the effects of swamp eels and other large predatory fishes in Taylor Slough using their catch-per-unit-effort (CPUE; # individuals caught per 5-minute transect) in an electrofishing dataset. These analyses were performed on a dataset that included only nine plots in Taylor Slough because four of the thirteen plots in Taylor Slough were not sampled by electrofishing, while dry-season electrofishing sampling is limited most years because airboats cannot access sites (throw-trap sampling continues when accessed by helicopter). To partially overcome limitations of missing dry-season sampling, we created indices of annual predator CPUE caught via electrofishing by averaging the total number of fish caught across all electrofishing transects during both wet-season sampling periods (July, October). These annual indices were used as predictor variables in analyses.

We used the same parameterized models of the baseline period prior to swamp eel invasion described in the main text to set the hydrological covariates used in models. We then analyzed the entire dataset, including the ‘during’ period that was excluded from ‘before/after’ analyses in the main text. We maintained the hydrological covariates and annual index of swamp eel CPUE in all models and used a model-selection approach to determine whether Mayan Cichlids (*Mayaheros urophthalmus*) and a group of ‘top predators’ should be included in the model with the two non-native species. These top predators were the three most common large native fishes in the Everglades: *Amia calva* (Bowfin), *Lepisosteus platyrhincus* (Florida Gar), and *Micropterus salmoides* (Largemouth Bass). Mayan cichlids and top predators were only included in models when the AIC was ≥2 than the base model (hydrologic variables + swamp eels).

All analyses were mixed-effects models that included plot nested within site as a random effect. Dependent variables were densities of each species and were log-transformed to approximate normal error distributions of the models’ fit. Independent variables length of the previous dry season (LDS) and days since dry (DSD) were log transformed, depth was not transformed, and models were fit with a gaussian distribution to best meet model assumptions (normality of error distributions) and achieve best model fit. All models were fit by maximum likelihood (using the Satterthwaite method) with the lme4 v 1.1-30 and lmerTest v 3.1-3 packages in R v 4.2.1 (Bates et al., 2015; Kuznetsova et al., 2017; R Core Team, 2022).

Results of these analyses (Table S3) illustrated that there were significant negative relationships between swamp eel CPUE and the densities of the three species with the most dramatic population declines (*Procambarus alleni*, *Procambarus fallax*, *Jordanella floridae*), while neither Mayan Cichlids nor top predators were significantly negatively associated with the declines in these species. Higher swamp eel densities were also significantly associated with lower densities of the other species we observed population declines in: *Fundulus chrysotus*, *Fundulus confluentus*, and *Gambusia holbrooki*. There were also significant negative associations between higher Mayan Cichlid densities and densities of *F*. *confluentus* and *G*. *holbrooki*, however these effect sizes were much smaller than those of swamp eels. Additionally, analyses of predator effects restricted to the baseline period prior to swamp eel arrival when Mayan Cichlids were the most common fish in the system detected no effects of Mayan Cichlids on any of our species analyzed here (Pintar et al. unpublished data). While Mayan Cichlids may certainly be adding predation pressure to these species, it is also possible their densities here are simply capturing residual variation in prey densities that is not fully accounted for by swamp eel densities. Our electrofishing CPUE of large fish densities may not adequately capture the effects of both of these predators in the Everglades, and we also expect that the mere presence of swamp eels throughout Taylor Slough has altered the system beyond which any historic variation in Mayan Cichlid densities did.

Higher densities of swamp eels were significantly associated with higher densities of *Palaemonetes* [*Palaemon*] *paludosus* and *Heterandria formosa*. However, both of these effects were small and both species positively respond to lengthening hydroperiod, and so in this case swamp eel densities may be capturing residual positive hydrologic covariation. Similarly, *P*. *fallax*, *F*. *chrysotus*, *G*. *holbrooki*, *H*. *formosa*, *J.* *floridae*, and *L*. *goodei* had significant positive relationships with higher CPUE of top predators. These positive relationships were typically smaller in magnitude (standardized coefficients) than those of swamp eels and hydrologic variables; we expect that they occur because it is difficult to completely separate hydrologic variation from variation in populations of most predator species in a system with brief predator-free periods. Hence, prey species that typically positively respond to wetter conditions may have residual hydrologic covariation that is captured by top predator populations, which are also typically higher in wetter periods (i.e., hydrologic drought is a “net” disturbance for both prey and their predators).

The three primary regions sampled for this project (Taylor Slough, Shark River Slough, Water Conservation Area 3A) have differences in hydrology and ecology, but Shark River Slough is more similar to Taylor Slough than is Water Conservation Area 3A. Both Shark River Slough and Water Conservation Area 3A can serve as reference regions to compare the changes that we have documented in Taylor Slough (Hargrove & Pickering, 1992). Such ‘natural field experiments’ enable comparison of landscape-scale changes in natural settings. We have documented drastic landscape-scale declines in the populations of four species in Taylor Slough (Fig. 2) that correlate strongly with the invasion of swamp eels in that region; data from the eastern marl prairies of the Panhandle region (Figs. S2, S3) tell a similar story. Comparison of the data in Taylor Slough and the Panhandle to Shark River Slough (Fig. S4) and Water Conservation Area 3A (Fig. S5), regions in which swamp eels were not detected until late 2019 or more recently (Fig. S2), show that there have been no system-wide collapses in the populations of any species across the entirety of the project period. Changes in species populations in these regions are responsive to regional and local hydrology interacting with the biology/phenology of each species. The effects of swamp eels in Shark River Slough and the Water Conservation Areas may depend on the population/species present in each region (originating from Homestead or North Miami; Collins et al. 2002, Schofield and Nico 2009) and their interaction with the hydrology and biology of each of these regions. As the invasion runs its course, continued monitoring of animal populations in these regions will be important for understanding the ecosystem-level effects of swamp eels in the Everglades.

**Appendix S2:**

*Supporting tables and figures*

**Table S1.** List of the six most common small fishes and three most common decapods during the ‘before’ period (1996–2009) prior to swamp eel arrival in Taylor Slough, along with their total abundances (Abund.) and average densities (Dens. = #/m2) during the before, during, and after periods. Species are listed in declining order of abundance during the ‘before’ period. Unidentified crayfish were typically those too small to be identified to species (< 8 mm carapace length; see Dorn and Trexler 2007) and are included here for illustrative purposes but were not individually analyzed. The sampling effort during each period is not equivalent in terms of both number of years sampled and within-year sampling, which is why analyses are performed on densities illustrated in Fig. 2. However, this table is intended to simply show the overall abundances before versus after invasion.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Species | Before (1996–2009) | | During (2010–2014) | | After (2015–2022) | |
|  | Abund. | Dens. | Abund. | Dens. | Abund. | Dens. |
| *Palaemonetes paludosus* (Grass Shrimp) | 32,241 | 6.04 | 5,803 | 3.03 | 27,278 | 9.43 |
| *Lucania goodei* (Bluefin Killifish) | 14,130 | 2.66 | 5,667 | 2.96 | 13,983 | 4.46 |
| *Procambarus alleni* (Everglades Crayfish) | 8,465 | 1.81 | 1,783 | 0.98 | 12 | 0.00 |
| *Gambusia holbrooki* (Eastern Mosquitofish) | 7,588 | 1.43 | 2,751 | 1.49 | 2,006 | 0.65 |
| *Jordanella floridae* (Flagfish) | 7,497 | 1.41 | 1,439 | 0.75 | 52 | 0.02 |
| *Heterandria formosa* (Least Killifish) | 7,006 | 1.27 | 1,476 | 0.77 | 5,732 | 1.82 |
| *Fundulus chrysotus* (Golden Topminnow) | 3,542 | 0.68 | 1,308 | 0.68 | 1,519 | 0.50 |
| *Procambarus fallax* (Slough Crayfish) | 2,404 | 0.45 | 263 | 0.15 | 4 | 0.00 |
| *Fundulus confluentus* (Marsh Killifish) | 1,390 | 0.30 | 454 | 0.23 | 42 | 0.01 |
| *Procambarus* spp. (Unidentified crayfish) | 1,169 | 0.25 | 165 | 0.09 | 6 | 0.00 |

**Table S2.** Results of mixed effects models from the parameterization of hydrological effects during the baseline period (before swamp eel invasion; 1996–2009) for the three most common decapods and six most common fishes in Taylor Slough. Parameters were selected based on a model selection procedure described in the methods of the main text. Season indicates the sampling month (unordered categorical variable), depth is the average depth over the prior 30 or 180 days, LDS is the length of the previous dry season, DSD is the days since a plot was last dry (depth < 5 cm). Bold indicates statistical significance (*P* < 0.05).

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | Coef. | df | F | *P* |
| *Palaemonetes paludosus* (Grass Shrimp): = 0.057, = 0.253 | | | | |
| season | **-0.175**, **-0.348**, **-0.276**, **-0.118** | 4, 762 | 10.1 | **<0.0001** |
| 180-day depth | **0.278** | 1, 633 | 24.6 | **<0.0001** |
| *Procambarus alleni* (Everglades Crayfish): = 0.275, = 0.514 | | | | |
| season | **-0.149**, **-0.229**, **-0.188**, **-0.153** | 4, 762 | 4.5 | **0.0014** |
| LDS | **0.487** | 1, 759 | 42.5 | **<0.0001** |
| DSD | **-0.217** | 1, 760 | 26.6 | **<0.0001** |
| 180-day depth | **0.219** | 1, 762 | 17.8 | **<0.0001** |
| season:LDS | **-0.120**, **-0.186**, **-0.207**, **-0.201** | 4, 758 | 6.5 | **<0.0001** |
| *Procambarus fallax* (Slough Crayfish): = 0.097, = 0.329 | | | | |
| season | **-0.180**, -0.014, **0.151**, 0.032 |  | 11.5 | **<0.0001** |
| DSD | **0.168** |  | 25.3 | **<0.0001** |
| 30-day depth | 0.084 |  | 2.5 | 0.11 |
| *Fundulus chrysotus* (Golden Topminnow): = 0.340, = 0.409 | | | | |
| season | 0.062, -0.005, **-0.138**, **-0.107** | 4, 725 | 5.0 | **0.0005** |
| LDS | **-0.364** | 1, 765 | 76.0 | **<0.0001** |
| DSD | **0.303** | 1, 765 | 45.6 | **<0.0001** |
| 30-day depth | **-0.114** | 1, 476 | 5.6 | **0.018** |
| *Fundulus confluentus* (Marsh Killifish): = 0.116, = 0.139 | | | | |
| DSD | **-0.317** | 1, 753 | 87.5 | **<0.0001** |
| 30-day depth | **-0.106** | 1, 734 | 9.6 | **0.0020** |
| *Gambusia holbrooki* (Eastern Mosquitofish): = 0.118, = 0.308 | | | | |
| LDS | -0.080 | 1, 767 | 3.6 | 0.059 |
| DSD | **0.193** | 1, 766 | 17.3 | **<0.0001** |
| 180-day depth | **0.138** | 1, 715 | 12.5 | **0.0004** |
| *Heterandria formosa* (Least Killifish): = 0.383, = 0.520 | | | | |
| season | **0.146**, **0.161**, **0.137**, **0.094** | 4, 759 | 3.3 | **0.011** |
| LDS | **0.102** | 1, 767 | 27.1 | **<0.0001** |
| DSD | **0.496** | 1, 764 | 136.7 | **<0.0001** |
| season:LDS | **-0.238**, **-0.282**, **-0.245** **-0.197** | 1, 760 | 8.5 | **<0.0001** |
| *Jordanella floridae* (Flagfish): = 0.086, = 0.109 | | | | |
| season | **-0.289**, **-0.282**, **-0.255**, **-0.325** | 4, 763 | 18.5 | **<0.0001** |
| LDS | **0.107** | 1, 770 | 8.3 | **0.0041** |
| *Lucania goodei* (Bluefin Killifish): 0.618, = 0.738 | | | | |
| season | **0.110**, **0.168**, **0.171**, **0.127** | 4, 762 | 5.9 | **0.0001** |
| LDS | **-0.401** | 1, 759 | 324.9 | **<0.0001** |
| DSD | **0.260** | 1, 761 | 72.9 | **<0.0001** |
| 180-day depth | 0.068 | 1, 731 | 3.4 | 0.068 |
| season:LDS | **-0.101**, **-0.101**, **-0.083**, -0.057 | 4, 759 | 2.1 | 0.074 |

**Table S3.** Results of mixed effects analyses using the CPUE of large predatory fishes in Taylor Slough during the entirety of the sampling period (1996–2022) for the three most common decapods and six most common fishes. Hydrologic parameters are the same as those included in our final model of the baseline period (S3). Swamp eels and Mayan Cichlids were always retained in models regardless of fit because they were the primary predators of interest, while top predators were excluded based on model selection described in the Appendix S1. Species are listed in descending order of abundance. Coefficients are the standardized (beta) regression coefficients. Season indicates the sampling month (unordered categorical variable), depth is the average depth over the prior 30 or 180 days, LDS is the length of the previous dry season, DSD is the days since a plot was last dry (depth < 5 cm). MC are effects of Mayan Cichlids (*Mayaheros urophthalmus*). Other variables are effects of the taxa as described above. Bold indicates statistically significant effects (*P* < 0.05).

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | Coef. | df | F | *P* |
| *Palaemonetes paludosus* (Grass Shrimp): = 0.060, = 0.281 | | | | |
| season | **-0.140**, **-0.256**, **-0.259**, **-0.092** | 4, 1072 | 10.9 | **<0.0001** |
| 180-day depth | **0.239** | 1, 1076 | 341.8 | **<0.0001** |
| swamp eels | **0.083** | 1, 1083 | 8.3 | **0.0040** |
| MC | 0.035 | 1, 1080 | 1.7 | 0.20 |
| *Procambarus alleni* (Everglades Crayfish): = 0.349, = 0.407 | | | | |
| season | **-0.106**, **-0.168**, **-0.165**, **-0.127** | 4, 1095 | 3.7 | **0.0057** |
| LDS | **0.614** | 1, 1103 | 79.1 | **<0.0001** |
| DSD | **-0.146** | 1, 1101 | 10.9 | **0.0010** |
| 180-day depth | **0.125** | 1, 980 | 7.8 | **0.0052** |
| season:LDS | **-0.128**, **-0.177**, **-0.184**, **-0.217** | 4, 1092 | 7.1 | **<0.0001** |
| swamp eels | **-0.210** | 1, 1098 | 63.3 | **<0.0001** |
| *Procambarus fallax* (Slough Crayfish): = 0.134, = 0.268 | | | | |
| season | -0.029, 0.025, 0.069, **-0.091** | 4, 1093 | 6.3 | **<0.0001** |
| DSD | **0.074** | 1, 1098 | 5.8 | **0.016** |
| 30-day depth | **-0.141** | 1, 1099 | 9.7 | **0.0019** |
| swamp eels | **-0.294** | 1, 1105 | 102.3 | **<0.0001** |
| Top Preds | **0.119** | 1, 1102 | 19.6 | **<0.0001** |
| *Fundulus chrysotus* (Golden Topminnow): = 0.208, = 0.296 | | | | |
| season | **0.176**, 0.028, **-0.176**, **-0.219** | 4, 1085 | 19.0 | **<0.0001** |
| LDS | **-0.314** | 1, 1093 | 55.4 | **<0.0001** |
| DSD | **0.190** | 1, 1095 | 18.0 | **<0.0001** |
| 30-day depth | **-0.346** | 1, 1022 | 58.9 | **<0.0001** |
| swamp eels | **-0.062** | 1, 1076 | 4.7 | **0.030** |
| Top Preds | **0.123** | 1, 977 | 21.3 | **<0.0001** |
| *Fundulus confluentus* (Marsh Killifish): = 0.131, = 0.164 | | | | |
| DSD | **-0.252** | 1, 1097 | 73.0 | **<0.0001** |
| 30-day depth | **-0.059** | 1, 1089 | 4.1 | **0.043** |
| swamp eels | **-0.152** | 1, 1083 | 24.0 | **<0.0001** |
| MC | **-0.072** | 1, 1071 | 6.1 | **0.014** |
| Top Preds | -0.041 | 1, 1046 | 2.1 | 0.14 |
| *Gambusia holbrooki* (Eastern Mosquitofish): = 0.051, = 0.249 | | | | |
| LDS | **0.102** | 1, 1089 | 6.2 | **0.013** |
| DSD | **0.168** | 1, 1090 | 14.3 | **0.0002** |
| 180-day depth | **0.068** | 1, 1094 | 4.2 | **0.040** |
| swamp eels | **-0.137** | 1, 1087 | 21.4 | **<0.0001** |
| MC | **-0.057** | 1, 1063 | 4.0 | **0.046** |
| Top Preds | **0.097** | 1, 1035 | 12.7 | **0.0004** |
| *Heterandria formosa* (Least Killifish): = 0.391, = 0.468 | | | | |
| season | **0.091**, **0.111**, 0.064, 0.033 | 4, 1083 | 2.7 | **0.028** |
| LDS | 0.276 | 1, 1090 | 0.6 | 0.43 |
| DSD | **0.624** | 1, 1095 | 222.7 | **<0.0001** |
| season:LDS | **-0.178**, **-0.230**, **-0.238**, **-0.219** | 4, 1084 | 10.0 | **<0.0001** |
| swamp eels | **0.058** | 1, 1096 | 5.5 | **0.020** |
| Top Preds | **0.088** | 1, 1073 | 14.3 | **0.0002** |
| *Jordanella floridae* (Flagfish): = 0.213, = 0.228 | | | | |
| season | **-0.135**, **-0.148**, **-0.190**, **-0.232** | 4, 1081 | 13.7 | **<0.0001** |
| LDS | **0.189** | 1, 1094 | 44.8 | **<0.0001** |
| swamp eels | **-0.290** | 1, 1062 | 97.7 | **<0.0001** |
| MC | -0.040 | 1, 1046 | 2.0 | 0.16 |
| Top Preds | **0.120** | 1, 995 | 19.1 | **<0.0001** |
| *Lucania goodei* (Bluefin Killifish): 0.470, = 0.708 | | | | |
| season | 0.066, 0.087, 0.065, 0.018 | 4, 1079 | 2.1 | 0.081 |
| LDS | **-0.506** | 1, 1084 | 244.0 | **<0.0001** |
| DSD | **0.204** | 1, 1081 | 40.0 | **<0.0001** |
| 180-day depth | **0.098** | 1, 1093 | 8.9 | **0.0030** |
| season:LDS | -0.011, 0.005, 0.035, **0.074** | 4, 1077 | 2.5 | **0.038** |
| swamp eels | **0.057** | 1, 1094 | 8.7 | **0.0033** |
| Top Preds | **0.039** | 1, 1085 | 4.3 | **0.028** |



**Figure S1.** Hydrological conditions in Taylor Slough in Everglades National Park from 1996–2022: (a) average 30-day depth, (b) average 180-day depth, (c) days since a plot was last dry (depth < 5 cm; DSD), and (d) the number of days each site was dry (depth < 5 cm) during the previous dry season (LDS). Data are displayed for all sampling periods used here (July, October, December, February) at all plots. Lines represent running means for each site (CP, MD, TS; Fig. 1) fit by the loess method in ggplot2 for illustration of general trends across years and between sites.



**Figure S2.** Log-transformed densities of swamp eels (*Monopterus* *albus*/*javanensis*) caught in the four regions of the Everglades during 1996–2022: (a) Taylor Slough (equivalent to Fig. 1b), (b) Panhandle, (c) Shark River Slough, and (d) Water Conservation Area (WCA) 3A. Blue triangles are plot-level mean catches via airboat-mounted electrofishing (scale is catch-per-unit-effort [CPUE]; # individuals / 5-minute transect). Purple circles are plot-level mean catches in 1-m2 throw traps (scale is # / m2). Lines are the region-wide mean densities of all plots during each sampling period for each sampling method; error bars are excluded for clarity. Note that during the latter part of the time series electrofishing in the Panhandle region has been very limited (at least one plot was sampled in only 5 of the last 17 sampling periods), so the scarcity of points after 2016 may give the impression that populations of swamp eels have fallen when this may just be a byproduct of our data limitations; Panhandle collecting also did not begin until 2008. The light shaded areas approximate the periods when swamp eels were spreading throughout each region, while the darker shaded area represents the period during which they have been established throughout Taylor Slough and the Panhandle.



**Figure S3.** Densities (log-transformed) of three decapods (a–c) and six small fishes (d–i) collected from 1-m2 throw traps in the Panhandle region of the Everglades during 2008–2022. These are the same taxa as analyzed from Taylor Slough in the main text and are presented here in the same order as Fig. 3. Point color indicates crustacean species (green) and fish species (blue). The black line is the mean density of all plots during each sampling period; error bars are excluded for clarity. Swamp eels were present during the entire study period, but were not common and established until after ~2012 (Fig. S2). The light shaded area approximates the period when swamp eels were spreading throughout the Panhandle, while the darker shaded area represents the period during which they have been established throughout the region.



**Figure S4.** Densities (log-transformed) of three decapods (a–c) and six small fishes (d–f) collected from 1-m2 throw traps in Shark River Slough of the Everglades during 1996–2022. These are the same taxa as analyzed from Taylor Slough in the main text and are presented here in the same order as Fig. 3. Point color indicates crustacean species (green) and fish species (blue). The black line is the mean density of all plots during each sampling period; error bars are excluded for clarity. The light shaded area represents the period from when swamp eels were first detected (late 2019) and through 2022 as they spread in Shark River Slough. The light shaded area approximates the period from when swamp eels were first detected and have since been spreading throughout Shark River Slough.



**Figure S5.** Densities (log-transformed) of three decapods (a–c) and six small fishes (d–f) collected from 1-m2 throw traps in Water Conservation Area 3A of the Everglades during 1996–2022. These are the same taxa as analyzed from Taylor Slough in the main text and are presented here in the same order as Fig. 3. Point color indicates crustacean species (green) and fish species (blue). The black line is the mean density of all plots during each sampling period; error bars are excluded for clarity. The light shaded area approximates the period from when swamp eels were first detected and have since been spreading throughout Water Conservation Area 3A.

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