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Research Article

Assessing *Salvinia molesta* impact on environmental conditions in an urban lake: case study of Lago Las Curias, Puerto Rico

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Abstract

Giant salvinia (*Salvinia molesta* Mitchell, Salviniaceae) is a free-floating fern native to Brazil that alters natural processes in aquatic ecosystems, causing ecological problems for water resource managers. Due to its ease of dispersal through fragmentation and rapid growth, giant salvinia can quickly become problematic, requiring persistent management efforts. If left unmanaged, giant salvinia creates a thick mat of vegetation, which limits sunlight penetration, reducing aquatic macrophytes, lowering dissolved oxygen and stressing aquatic organisms. Giant salvinia was first reported in Lago Las Curias, Cupey, San Juan, Puerto Rico, USA, in 2016 and covered the entire 19 ha waterbody in 2018. In 2019, we conducted surveys to examine the extent of the invasion and quantify ecological damage to the aquatic environment. We found that the lake is lacking in dissolved oxygen, with a mean concentration of 0.38 mg L^{-1}, and mean concentrations of nitrate, ammonium, and phosphate were < 1 mg L^{-1}. Mean pH in 2019 was 6.4, down from 7.6 in years prior to giant salvinia. We estimated total fresh giant salvinia biomass to be 3,449 metric tons and dry biomass to be 51 metric tons. Other floating vegetation associated with the giant salvinia mat included *Pistia stratiotes, Pontederia crassipes*, *Typha* sp., *Oxycaryum cubense*, *Cyperus esculentus* and *Mikania* sp. Uncontrolled growth of giant salvinia impeded access to the waterbody and degraded resource quality in the aquatic ecosystem. The lack of dissolved oxygen and decreasing pH creates conditions for sedimentary nutrients release, creating a potential internal loading of phosphorus. To control an infestation of this magnitude we suggest biological control with the salvinia weevil (*Cyrtobagous salviniae*) which has proven successful in controlling giant salvinia, and at a fraction of the cost of other control methods. Ultimately, an integrated management plan, including chemical and mechanical control, needs to be established to control giant salvinia and other invasive free-floating plants, and monitor the restoration of ecological services at Lago Las Curias. As a long term goal, nutrient fluxes into the lake must be reduced by eliminating non-point sources of pollution throughout the watershed.

Key words: aquatic invasive species, *Cyrtobagous salviniae*, giant salvinia, lake water quality

Introduction

Invasion by the free-floating aquatic fern *Salvinia molesta* Mitchell 1972 (giant salvinia; Salviniaceae) can rapidly alter ecosystem processes and functions in aquatic environments. Giant salvinia invades slow moving waterbodies, reproduces asexually through fragmentation (McFarland et al. 2004), and grows rapidly under ideal conditions doubling its biomass in as few as 36 h (Johnson et al. 2010). Native to Brazil, giant salvinia was first detected outside its native range in Sri Lanka in 1939 (Room 1990), and has been reported in 61 countries since (CABI 2019; Luque et al. 2014). Once giant salvinia infestation begins, this fern forms a thin mat of vegetation on the water surface. As growth continues the mat increases in thickness and biomass, ultimately forming a multilayer barrier between the terrestrial and aquatic environments. The mat can act as substrate, allowing terrestrial plants to colonize, eventually creating floating islands (or tussocks) composed of organic matter (Mallison et al. 2001). Nutrient concentration and pH have been reported as factors which influence giant salvinia biomass and percent cover (Owens and Smart 2010; Madsen and Wersal 2008). A giant salvinia mat prevents light penetration into the water, resulting in a loss of primary producers, reducing dissolved oxygen, thus altering the flow of energy in the waterbody (Rommens et al. 2003; McFarland et al. 2004). Over time, older giant salvinia fronds are shed from the mat and decompose at the bottom of the waterbody. Microbial breakdown of this detritus consumes dissolved oxygen (DO), leading to the loss of fish, crayfish, zooplankton, frog larvae and other aquatic organisms (Oliver 1993; Roman et al. 1993; Moore and Townsend 1998; Chaichana and Wanjit 2018). Additionally, thick mats of giant salvinia block navigation, limiting recreational boating, fishing and hunting (Julien et al. 2002). Giant salvinia mats can prevent boat passage, restricting access to fishing or waterfowl hunting grounds. This could result in an economic impact as these recreational activities become unavailable.

Due to the absence of natural enemies and rapid growth, controlling giant salvinia is a major challenge in adventive ranges. When attempting to control small infestations, mechanical harvesters, lake drawdowns, and herbicide applications can be adequate, with chemical control being the most rapid and effective (Mudge et al. 2014). These modes of control, however, become ineffective and costly for large infestations (Julien et al. 2009). A cost effective and sustainable method to control large scale infestations is biological control using *Cyrtobagous salviniae* Calder and Sands, 1985 (salvinia weevil; Coleoptera: Curculionidae). Salvinia weevils have successfully controlled giant salvinia worldwide in subtropical and tropical regions. Releases of the salvinia weevil in Australia reduced giant salvinia coverage by more than 95% over 13 months (Room et al. 1981) and up to 99% after 21 months in the United States (Tipping et al. 2008).

Giant salvinia was first detected in Puerto Rico in 2000. Giant salvinia has been reported in San Juan, Carolina, Culebra and in the Mayaguez municipalities in Puerto Rico (Thayer et al. 2018). The invasion of giant salvinia in Lago Las Curias, located in the municipality of San Juan, limits recreational activities, resulting in potential economic loss, and reduces ecological benefits provided by the waterbody and downstream habitats. Giant salvinia first appeared in Lago Las Curias in 2016 (Thayer et al. 2018) and over the next three years, negatively impacted the local community (Marrero 2017; Garcia 2018). Due to the constant growing season provided by the tropical climate and the three year infestation at Lago Las Curias, we hypothesized that ecological conditions at the lake were drastically altered. The overarching goal of this study was to measure the impact of the giant salvinia invasion to the aquatic ecosystem in this tropical urban lake. The specific objectives were to measure coverage and biomass, determine the presence of natural enemies (biocontrol agents or other herbivorous insects), document the ecological impact to the waterbody, identify other plants associated with the mat, and establish a baseline of water and plant quality. Additionally, we provide suggestions about implementing a biological control program in Lago Las Curias and how to manage the infestation in the future.

Materials and methods

Site description

Lago Las Curias has a surface area of 19.2 ha, located in Cupey, San Juan, Puerto Rico, USA (N18.34169; W66.04828). The lake was built in 1946 by the Puerto Rico Aqueduct and Sewer Authority (PRASA) using an earthen dam, 22 m height, to provide a source of drinking water for the San Juan Metropolitan Area (García-Martinó 2000; Torres-Ortiz and Rosa-Castro 2014), estimated population of 856,367 people (U.S. Census Bureau, Population Division 2020), and has been managed by the PRASA since the early 1980s (Tetra Tech 2018). Lago Las Curias drainage area is approximately 285 ha, with watershed land use composed of forest (43%), grassland (36%), low-medium density residential (12%), and open space (4%) (Tetra Tech 2018). A 13 m diameter concrete overflow pipe maintains a constant water level of ~ 1,381,498 m^3 at ~ 100 m elevation (Tetra Tech 2018). The lake drains into the Quebrada Las Curias, which is a tributary of the Rio Piedras that discharges into the San Juan Bay. Historically, the lake offered abundant recreational opportunities such as bird watching, boating, kayaking, swimming, fishing, sightseeing, tourism (restaurants), among others. Two sampling trips were made to Lago Las Curias on 22 July and 27 September 2019. The first sampling date assessed conditions at six stations around the lake edge, and the second survey targeted eight stations in the middle of the waterbody (Figure 1).

Plant performance

Changes in percent giant salvinia coverage through time was determined with high resolution satellite imagery from Google Earth®, where polygons (using Google Earth® polygon tool) were created around the visible giant

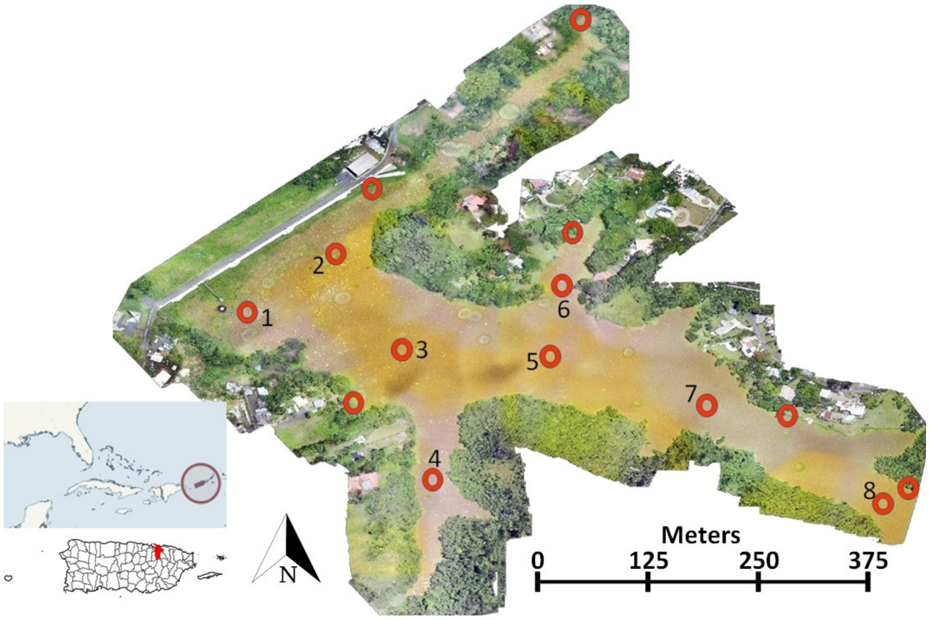

Figure 1. Drone image of Lago Las Curias, Puerto Rico on 22 July 2019 showing the complete coverage of giant salvinia. Circles indicate shoreline and middle of the lake sampling stations. Stations located in the middle are identified with numbers, while shoreline stations are not numbered. Lago Las Curias has a surface area of 19.2 ha and a watershed area of 280 ha, with no major tributaries draining into the lake. The land use in the watershed is primarily forest, grassland, and urban development. Water flows out of the lake via a concrete outflow pipe, in the northwestern part of the lake near middle station 1.

salvinia mat to determine coverage area. Reports by local residents, personal observations (J. Ortiz) and media outlets confirmed a monoculture of giant salvinia was the plant present in satellite imagery (Marrero 2017; Garcia 2018). Previous studies have used Google Earth® to map vegetation (Song et al. 2018), to survey rock glaciers (Charbonneau and Smith 2018), and map landslides (Rabby and Li 2019). We examined Google Earth® imagery through time, starting from the initial recorded infestation in 2016 until the lake was 100% covered with giant salvinia.

To estimate giant salvinia biomass, we used a modified plastic quadrat, constructed from a PVC frame and a plastic container with the bottom removed (0.35 × 0.21 × 0.17 m; L × W × H; surface area 0.07 m^2). At each station, we pressed the quadrat in the vegetation mat and all giant salvinia plant matter within the frame was collected. While removing plant material, the quadrat was pushed further into the mat to prevent plants entering from outside of the frame. Ten buds were visually examined for feeding damage from samples removed from the quadrat (Van Oosterhout 2006). After collection, fresh biomass was determined by draining giant salvinia of water for 10 minutes before recording weight. To determine dry weight, giant salvinia was placed in a drying oven at 70 °C for 72 h then weighed.

Giant salvinia quality was determined at each station prior to removing plants from the modified quadrat. Percent green was visually estimated within the quadrat and a normalized difference vegetative index (NDVI) was determined using a handheld Trimble GreenSeeker® (Trimble Agriculture

Company, Sunnyvale, CA, USA). GreenSeeker was held 1.2 m above the mat surface then swept laterally for 1 m across the mat. Mat thickness was determined at each station by using a sinkable plastic tray (0.3 × 0.4 m), with a rope, marked in 1 cm increments, attached to the middle of the tray. The tray was slid through the giant salvinia to the bottom of the mat, then lifted to lay flat against the bottom of the mat, and length to the top of the mat was recorded. Plant species growing in the water or on top of the giant salvinia mat were identified at each station within a five meter radius of the station.

Insects associated with giant salvinia

To determine the presence of natural enemies, each giant salvinia biomass sample was placed in Berlese funnels (Boland and Room 1983). After recording fresh weight and prior to placing the plant material in the drying oven, giant salvinia was placed in the Berlese funnels for 72 h, and escaping insects were preserved in 80% ethanol. Samples were visually inspected for insects and, if present, identification was determined under a dissecting scope.

Water quality

Physico-chemical parameters including pH, DO, specific conductivity, and temperature were collected at all stations with a MiniSonde multiparameter sensor (Hydrolab Corp, Loveland CO, USA). Concentration of ammonium (NH_4), nitrate (NO_3), and phosphate (PO_4) were determined at shoreline locations only (0.25 m depth) with a SL1000 (Hach Company, Loveland CO, USA) system. For middle lake stations, water quality was measured at the surface and vertically through the water column at 1 m increments.

We gathered historical water quality data in Lago Las Curias from the Puerto Rico Environmental Quality Board and the San Juan Bay Estuary Program (SJBEP; https://web.estuario.org) databases to compare to current conditions. Data from SJBEP database have been used to document mosquito-borne disease transmission (de Jesús Crespo et al. 2019), and by the environmental protection agency (EPA) to create a comprehensive conservation and management plan. The SJBEP program sampled pH, DO, specific conductivity, monthly using Hydrolab Quanta (OTT HydroMet, Loveland, CO USA) from 2014 to 2017. The SJBEMP sampled water nutrients once in 2014, then every six months until sampling ceased in July 2017 with only one round of water nutrient sampling for the year. Sampling was conducted from the end of the pier near station one (Figure 1). We used R statistical software (version 1.1.463) for analysis between groups. We performed an analysis of variance (ANOVA) to test for differences in water quality variables between years. Water quality variables were normally distributed and had equal variance, therefore ANOVA was selected. Specific conductivity was log transformed to improve normality. Tukey's HSD test was used to examine which years were different. We

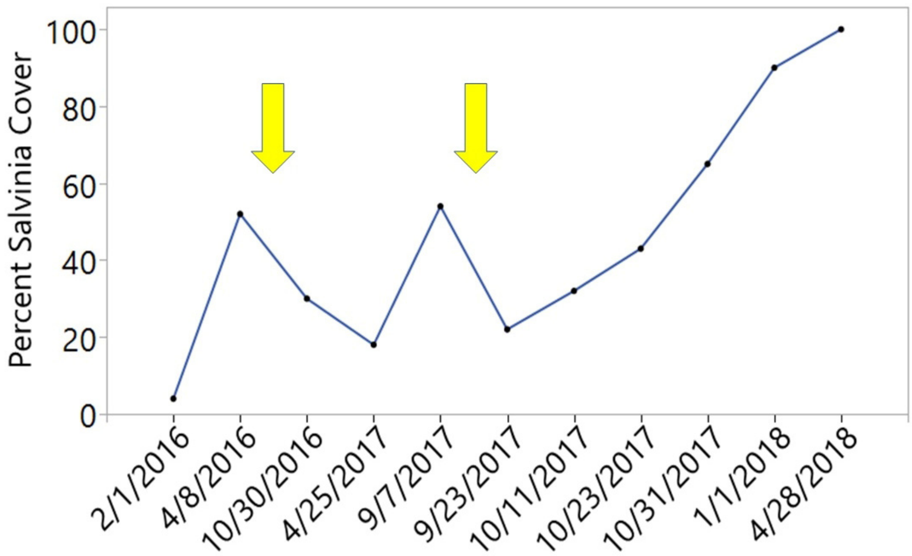

Figure 2. Percent cover of giant salvinia over time in Lago Las Curias, Puerto Rico. Yellow arrow after 8 April 2016 indicates beginning of efforts to remove salvinia. Second arrow after 7 September 2016 represents when hurricane Maria hit the island. The initial reduction in cover was due to giant salvinia flushing out of the lake, then coverage increased as efforts to remove salvinia ceased.

examined variables at similar depth (0.5 m) for all years and stations. JMP statistical software was used to produce graphs.

Results

Plant performance

Giant salvinia was first observed in Lago Las Curias in February 2016 and covered the entire waterbody in two years (Figure 2). The source of the initial introduction of giant salvinia into the lake was not determined. When first observed on 1 February 2016, giant salvinia covered 4% of the water surface, then increased to 52% on 8 April 2016. Efforts were then implemented by residents to mechanically remove the plant material using an aquatic plant harvester. Hurricane Maria made landfall in Puerto Rico on 20 September 2017 initially reducing giant salvinia coverage. As management efforts were shifted away from Lago Las Curias following the hurricane, giant salvinia coverage increased to 90% on 1 January 2018 and covered 100% of the lake shortly after. Since then giant salvinia continued to cover 100% of the lake through September 2019. The thick giant salvinia mat made the lake inaccessible for recreational activities, while herbaceous plants, vines, and shrubs had colonized the mat (Figure 3).

A large amount of giant salvinia biomass was present across the entire lake. Mean fresh (wet) weight of giant salvinia removed from the quadrat (area = 0.0735m^2) was 1,320.4 g (± 721.2; n = 14), and mean dry weight was 21.5g (± 9.8, n = 14). We estimated total fresh giant salvinia plant biomass within the lake to be 3,449 metric tons (51.16 metric tons dry weight). This estimation comes from using the mean giant salvinia biomass per quadrat

Figure 3. Salvinia mat and aquatic and herbaceous plants growing within and on top of the mat at Lago Las Curias, Puerto Rico during September 2019. The abundance of plants growing within and on top of salvinia was the greatest towards the dam. Photos by C. Wahl and R. Diaz.

to approximate biomass per square meter, then scaled up to whole lake area. Mean mat thickness was 22 cm (± 9.8; n = 14), mean percent green was 67% (± 22.6; n = 14) and mean NDVI was 0.53 (± 0.01; n = 8). All giant salvinia buds checked were healthy, with no feeding damage or browning (n = 140). Berlese funnel extractions found that *Samea multiplicalis* Guenée, 1854, a generalist aquatic plant herbivore moth (Knopf and Habeck 1976), was present at two shore sampling locations. No salvinia weevils were present in the samples.

Herbaceous and free-floating plants

Herbaceous and free-floating plants were present among the giant salvinia mat (Figure 4). The free-floating invasive plants, *Pistia stratiotes* Linnaeus, 1753 (Figure 4A), and *Pontederia crassipes* Mart. Solms, 1883 (Figure 4B), were commonly found within the giant salvinia mat, especially at the northwestern edge of the lake. Emergent plants such as *Typha* sp. (Figure 4C), sedges, such as *Oxycaryum cubense* Poepp. & Kunth Lye, 1837 and *Cyperus esculentus* Linnaeus, 1953 (Figure 4D), terrestrial grasses (Figure 4E), and vines, such as *Mikania* sp. (Figure 4F) were abundant among the giant salvinia mat, adding to the amount of plant biomass on the lake.

Water quality

Data from 2014–2017 were examined to establish baseline water quality conditions prior to giant salvinia impact. Mean DO during this period was 5.18 mg L^{-1} [± 2.04 (± SD); n = 35], mean pH was 7.62 (± 0.50; n = 35), and mean specific conductivity was 265 (± 27; n = 35) (Table 1). Mean total Kjeldahl nitrogen was 0.80 mg L^{-1} (± 0.38; n = 4), mean total nitrogen (NO_3 and NO_2) was 0.08 (± 0.07; n = 5), mean total phosphorus (P) was 0.03 mg L^{-1} (± 0.01; n = 5), and mean ammonia (NH_3) was 0.04 (± 0.01; n = 3) (Table 1).

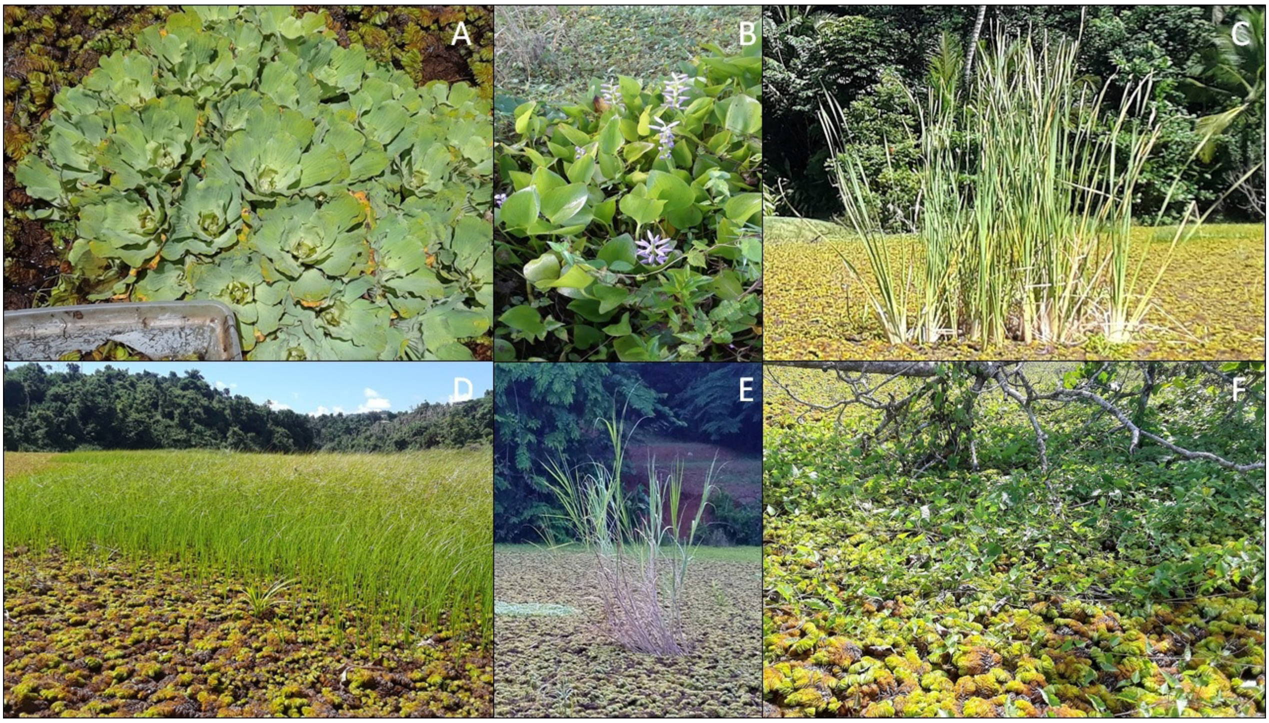

Figure 4. Free-floating invasive plants and terrestrial herbaceous plants including, *Pistia stratiotes* (A), *Pontederia crassipes* (B), *Typha* sp. (C), *Cyperus esculentus* (D), terrestrial grasses (E), and *Mikania* sp. (F) growing on top or within giant salvinia mats in Lago Las Curias, Puerto Rico. Photos by C. Wahl and R. Diaz.

Table 1. Mean water quality variables (± SD) in Lago Las Curias, Puerto Rico, for four years prior to giant salvinia infestation. Data were collected by the San Juan Bay Estuary Program.

Variable	2014	2015	2016	2017
DO (mg L^{-1})	5.42 (± 0.88, n = 6)	6.86 (± 2.46, n = 10)	4.03 (± 1.33, n = 12)	4.56 (± 1.66, n = 7)
pH	7.24 (± 0.53, n = 6)	7.93 (± 0.49, n = 10)	7.57 (± 0.42, n = 12)	7.62 (± 0.39, n = 7)
Sp. Cond (µS)	270 (± 6, n = 6)	280 (± 26, n = 10)	260 (± 30, n = 12)	250 (± 31, n = 7)
Mean Total N (mg L^{-1})	0.06 (n = 1)	0.05 (± 0.05, n = 2)	0.08 (± 0.10, n = 1)	0.17 (n = 1)
Mean NH_3 (mg L^{-1})	0.04 (n = 1)	0.03 (n = 1)	0.05 (n = 1)	–
Mean PO_4 (mg L^{-1})	0.03 (n = 1)	0.03 (± 0.02, n = 2)	0.02 (n = 2)	0.05 (n = 1)

Mean fecal coliform was 642 CFU 100 ml^{-1} (± 1,044; n = 5) and mean fecal enterococci was 1,148 CFU 100 ml^{-1} (± 1,279; n = 5).

Sampling in 2019 demonstrated that the giant salvinia infestation has changed water quality in Lago Las Curias. Mean DO along the shoreline stations was 0.08 mg L^{-1} (± 0.06; n = 6). Surface DO in the middle of the lake had a mean of 3.49 mg L^{-1} (± 2.10; n = 8). Mean DO was ≤ 0.13 mg L^{-1} at 0.5 m or greater depth for each station (Figure 5A). Mean pH along the shoreline was 6.99 (± 0.09, n = 6), surface pH in the middle of the lake ranged from 6.80–6.34 (n = 8) and decreased as depth increased. Mean pH at the deepest point of each vertical transect was 6.39 (± 0.02; n = 8) (Figure 5B). Mean water temperature along the shoreline was 25.7 °C (± 0.6; n = 6) and at the surface of the middle stations was 27.2 °C (± 0.9; n = 8) (Figure 5C). Temperature decreased at a rate of 0.7 °C per meter between surface and 4 m depth. Mean water temperature at ≥ 4 m was 23.5 °C (± 0.1; n = 44) (Figure 5C). Mean specific conductivity along the shoreline was 281 µS (± 51.51; n = 6), mean surface conductivity in the middle of the lake

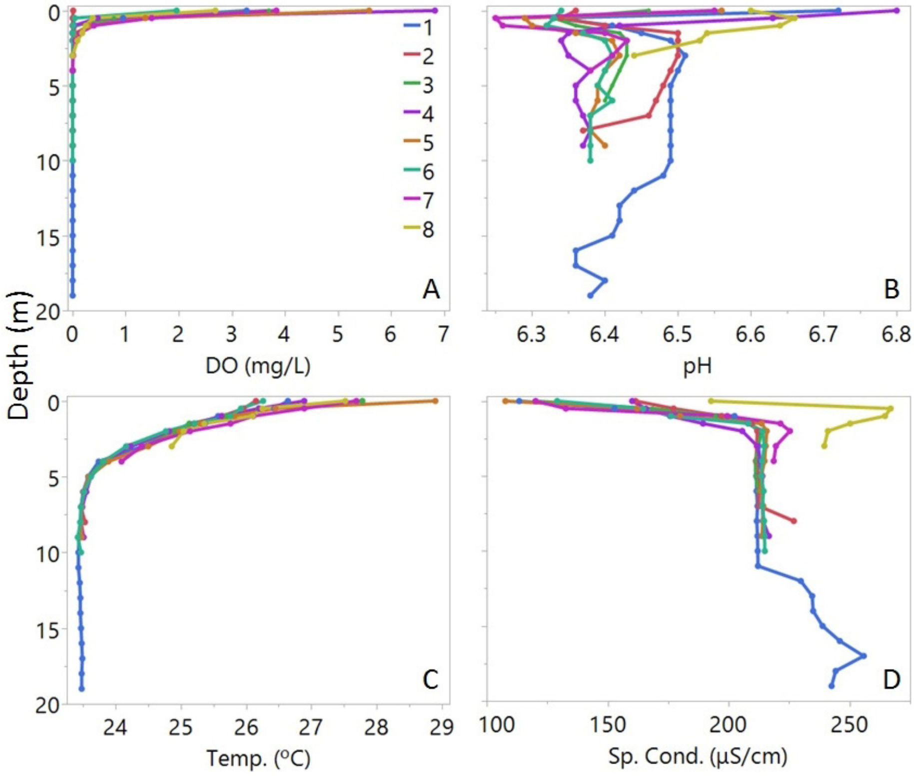

Figure 5. Vertical profiles of dissolved oxygen (A), pH (B), temperature (C), and specific conductivity (D) at the eight sampling sites in the middle of Lago Las Curias, Puerto Rico on 27 September 2019.

was 138 µS (± 30; n = 8), 199 µS (± 39.90; n = 8) at 1 m, and 215 µS between 1.5 and 11 m (± 8.21) (Figure 5D). Mean nutrient concentrations along the shoreline were 0.90 mg L^{-1} (± 0.37; n = 5) for NO_3, 0.16 mg L^{-1} (± 0.13; n = 5) for NH_4, and 0.36 mg L^{-1} (± 0.13; n = 4) for PO_4.

Water quality variables differed between years prior to giant salvinia infestation and during infestation. Analysis of variance indicated differences between years for DO ($F = 14.94$, $p < 0.0001$), pH ($F = 4.753$, $p < 0.0001$) and temperature ($F = 3.04$, $p = 0.002$). In 2019, DO had a mean less than 0.7 mg L^{-1} (± 0.91; n = 14) and was at least 6.2 times less compared to all other years (Figure 6A). Mean pH in 2019 was less than 6.5 (± 0.32; n = 14) and was 1.1 times lower compared to all other years (Figure 6B). In 2019, temperature was 26.1 °C (± 0.56; n = 14) and mean specific conductivity was 208 (± 74.6; n = 14), neither was different from all previous years (Figure 6C, D).

Discussion

Due to the complete coverage, biomass (3,449 metric tons) and mat thickness (~ 22 cm), we speculate that the giant salvinia infestation reached its maximum growth at Lago Las Curias. The tropical climate of Puerto Rico allows the constant production of fronds at the top of the mat and shedding of older fronds which sink and accumulate on the lake bottom (Room and Thomas 1986). The rate of decomposition of giant salvinia,

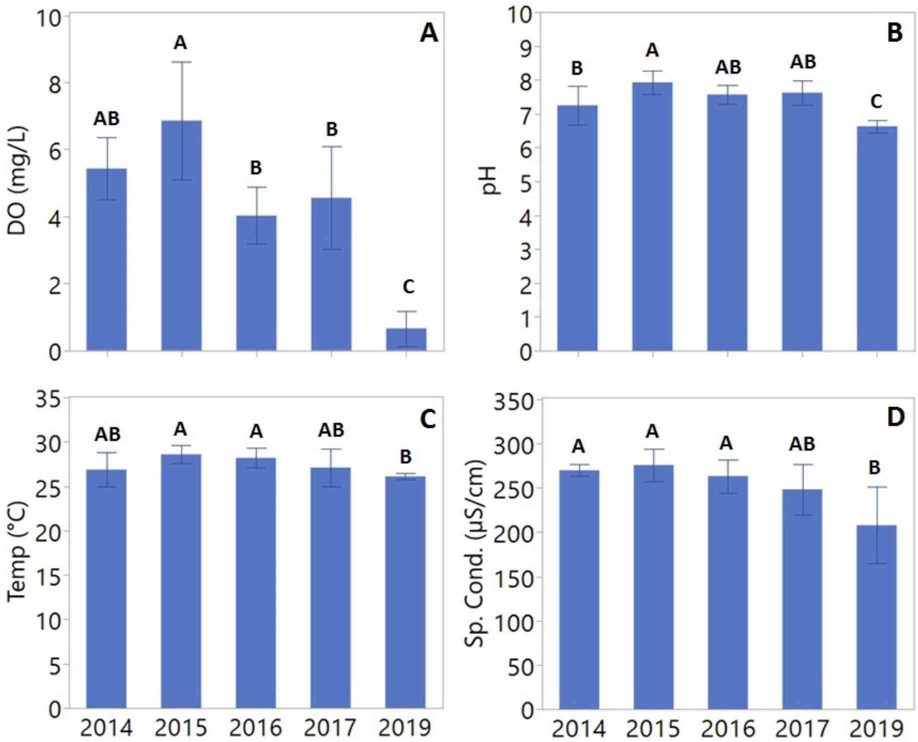

Figure 6. Bar graphs of dissolved oxygen (A), pH (B), temperature (C), and specific conductivity (D) over time in Lago Las Curias, with 95% confidence intervals. Letters represent statistically different groups. Water samples at 0.5 m depth were examined. In 2019, shoreline and middle lake stations were included.

however, is slow leading to an accumulation of detritus at the bottom of the lake (Sharma and Goel 1986). In addition to the change in water quality, giant salvinia detritus can reduce habitat quality in the lake. Giant salvinia detritus will buildup on the lake bottom, reducing depth, and smothering available habitat, potentially limiting access to spawning grounds for species of fish (Sullivan and Postle 2012). The colonization of terrestrial plants in the giant salvinia mat could result in the creation of floating islands. As plants grow within the mat, organic matter becomes trapped which provides substrate for additional plants. Floating islands have similar ecological impacts as giant salvinia mat, however biomass of the floating islands is greater and may require 2–3 times more effort to control than floating aquatic vegetation (Mallison and Hujik 1999).

Depletion of DO following giant salvinia infestation has been well documented (Oliver 1993; Flores and Carlson 2006; Tipping et al. 2008). Prior to the invasion of giant salvinia, DO in Lago Las Curias was above 4 mg L^{-1} and concentrations below 3 mg L^{-1} were not recorded until giant salvinia was introduced. Our surveys in 2019 found that DO in the lake was almost nonexistent with a mean of 0.65 mg L^{-1}. As giant salvinia infestation persists, older fronds are shed, which sink and accumulate on the lake bottom. This detritus is broken down by microbial processes, which consumes DO from the water, eventually creating hypoxic or anoxic conditions (Niyogi et al. 2003). Aquatic life becomes stressed when DO falls below 5 mg L^{-1} and large-fish kills can occur below 2 mg L^{-1} (Flores and Carlson 2006).

Indirectly, a constantly growing giant salvinia mat could further impair the ecosystem through nutrient release from the sediment. The anoxic environment can cause phosphorous (P) to be unbound from the sediment and released into the water column (Golterman 2001; Søndergaard et al. 2003). Masifwa et al. (2004) found that decomposing *P. crassipes* tissue released P into the water column, additionally the concentration and rate of release was enhanced when DO was < 1 mg L^{-1}. Previous research has found that the release of P from the sediment can be controlled by numerous factors, such as pH, temperature, iron levels; and the mechanisms vary with lake depth and geographic location (Søndergaard et al. 2003; Wu et al. 2014). With the low DO concentration and decreasing pH in Las Curias, release of P from sediments and plant tissues could be supplying nutrients to exacerbate biomass growth of giant salvinia and other floating invasive plants (Pinto and O'Farrell 2014; Wu et al. 2014). Mean total P recorded by SJBEMP in the years prior to giant salvinia impact was 0.03 mg L^{-1}, but this increased to 0.36 mg L^{-1} by July 2019, which could be the result of internal loading of P. Additional sampling, including total P and orthophosphate (Ortho-P), needs to be conducted to better understand the role of P release in Lago Las Curias.

The pH of Lago Las Curias decreased during the invasion of giant salvinia. Mean pH from 2014–2017 was 7.6 and values below 7.0 were not recorded by SJBEMP in the years prior to giant salvinia introduction. Mean pH during sampling in 2019 was 6.63, with 6.25 being the lowest recorded value. Decrease in pH has been recorded for other free-floating invasive aquatic plants, such as *Azolla filiculoides* Lamarack, 1783 (Janes et al. 1996), *P. stratiotes* (O'Farrell et al. 2011), and *P. crassipes* (Mahmood et al. 2005). Moreover, this decrease in pH creates more favorable conditions for giant salvinia since its biomass increases at pH levels ranging from 5 to 6 compared to 7 to 8 (Cary and Weerts 1984). pH decreases further through the accumulation and decomposition of giant salvinia (Owens et al. 2005), thus creating more favorable conditions for itself and decreasing competition from other species (Madsen and Wersal 2008). The lowest pH values were consistently found on the bottom of the lake where giant salvinia detritus was accumulating. Another explanation for the decrease in pH could be that the giant salvinia mat limits gas exchange, allowing carbon dioxide to accumulate in the water column, resulting in the acidification of the water column (Julien et al. 2012). The lowering of pH throughout an entire lake due to giant salvinia does not seem to be documented elsewhere. Connectivity and movement of water under giant salvinia mat in lakes and marshes may explain why lower pH in field infestations has not been observed. The watershed of Lago Las Curias is 285 ha and small tributaries enter the lake, therefore water movement in the lake is dependent on surface runoff from these small tributaries or direct rainfall entering the lake, and water can only exit when the lake is at full capacity.

Proper management techniques and a monitoring program need to be established to control giant salvinia in Lago Las Curias. In countries where funding to manage such invasions is limited, rapid implementation of control tactics is critical to mitigate ecological damage and reduce long term costs. To help mitigate the spread of giant salvinia, the implementation of biosecurity techniques, such as steam (Crane et al. 2019) or hot water (Anderson et al. 2015) exposure, have proven effective to inhibit the spread of non-native species on boats, trailers, and other equipment. The magnitude of the giant salvinia infestation makes controlling with chemical and mechanical methods unfeasible here. Biological control using the salvinia weevil has been proven as a safe method for long-term and large-scale control of giant salvinia in tropical and subtropical regions worldwide (Room et al. 1981; Cilliers 1991; Tipping et al. 2008), and seems to be the logical choice for Lago Las Curias. The salvinia weevil, a specialist herbivore native to Brazil, feeding specifically on species in the genus *Salvinia*, is approximately 2–3 mm in length and completes its life cycle within the giant salvinia mat (Room 1990). Warm temperatures and the presence of nitrogen-rich giant salvinia buds stimulate salvinia weevil reproduction, with female salvinia weevils laying eggs directly on new buds (Sands et al. 1986). Weevil larvae feed on young fronds, buds and root-like submerged leaves, then tunnel into the stem of the plant (Sands et al. 1983; Knutson and Mukherjee 2012). The tunneling action of the larvae ultimately damages the plant by limiting new growth, potentially exposing the plant to pathogens and causing the mat to sink (Tipping et al. 2008). The introduction of nonnative insects to control plant pests has inherent risk, however, due to the extensive host specificity tests conducted in Australia (Forno et al. 1983) and United States (Flores and Wendell 2001), and three decades of field data showing absence of non-target attack and success at controlling giant salvinia; we believe releasing *C. salviniae* is the best course of action in Lago Las Curias.

Proper release and management of salvinia weevils will be necessary to ensure their establishment and rapid impact. Releasing salvinia weevils in a cove, or confined portion, of the lake limits dispersal, resulting in locally high salvinia weevil density. Once salvinia weevil densities are approximately 50 weevils kg^{-1} at the release site, weevils can be transported around the lake to assist with dispersal. Releasing salvinia weevils at or about this density will ensure salvinia weevils can locate each other for reproduction, resulting in quick population growth at the release location. As the salvinia weevil density increases, giant salvinia quality and biomass will decrease, leading to a decline in salvinia weevil population. At this point an integrated management plan, using chemical, mechanical and biological control, should be implemented to further reduce and control giant salvinia outbreaks (Sullivan and Postle 2012). As giant salvinia decreases in biomass, implementing mechanical and chemical control will help increase the rate of loss.

Additionally, use of chemical control during periods of low biomass, or initial infestation, will help maintain open water and limit giant salvinia coverage. Active ingredients approved for aquatic use in the US, which are effective on giant salvinia, include glyphosate, diquat, fluridone, penoxsulam, and flumioxazin (Nelson et al. 2001; Mudge et al. 2012, 2016).

Integrated monitoring and management programs will need to be implemented to track recovery of ecosystem services and limit future impacts in Lago Las Curias. This will require the establishment, or appointing, of an agency to lead these efforts. The current lack of a responsible agency has led to the environmental degradation observed in Lago Las Curias. The reduction in giant salvinia biomass presents an opportunity for different invasive free-floating plants, such as *P. stratiotes* and *P. crassipes*, to take advantage of the available habitat. Detection and containment of such outbreaks before they become too problematic will be required. The altered ecological conditions due to giant salvinia invasion could produce conditions that favor establishment and spread other invasive species, known as invasion meltdown (Simberloff and Von Holle 1999). Nutrient loading in Lago Las Curias should be addressed to identify sources and reduce inputs. The environmental consulting report by Tetra Tech (2018) estimated an annual P load of 73.95 kg $year^{-1}$ and annual nitrogen load of 984.41 kg $year^{-1}$, not including sediment loads. They identified illicit discharges, nonpoint sources from failing or inappropriate septic systems, as a major contributor to high pollutant loads. Fecal coliform and fecal enterococci values recorded by SJBEMP suggested that discharges from septic systems are entering the lake. Strategies to manage septic system-sources, such as surveying/testing to find sources, repairing dilapidated systems, and education on nonpoint sources, should be conducted to identify and limit nutrient loading. Best management practices should be implemented to reduce nonpoint source nutrient loading in Lago Las Curias on a long-term basis. Our study is a critical initial step for the development of management plan of giant salvinia at Lago Las Curias. This management should include integration of weed control methods, and best practices for watershed monitoring. Water quality data prior to the giant salvinia invasion can be used as a benchmark for programs examining the recovery of the ecosystem.

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