

**REFINED ASSESSMENT OF WATER QUALITY IN MARINE AND FRESH WATERS
SURROUNDING SAG HARBOR VILLAGE, 2024**



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EXECUTIVE SUMMARY

Sag Harbor is a village located on eastern Long Island in New York, known for its historical and commercial importance. During the past decade, there has been increasing concern regarding water quality on eastern Long Island and studies from 2018 – 2023 revealed a series of water quality impairments within Sag Harbor including harmful algal blooms, hypoxia, and pathogenic bacterial contamination. Here, a follow-up study was designed to affirm water quality observations made from 2018 – 2023. In 2024, water samples were taken from three sites along Haven’s Beach, eleven marine sites, and ten storm drain sites. The sites were sampled for general water quality parameters (temperature, salinity, water clarity, and dissolved oxygen), fecal coliform bacteria and *Enterococcus* concentrations, total nitrogen levels, chlorophyll concentrations, harmful algal bloom densities, and sources of microbial bacteria. Results showed water quality observations to be largely consistent with prior monitoring, with primarily good water quality conditions. Though not anoxic, a majority of the sites along Haven’s Beach were rich in fecal coliform bacteria and *Enterococcus*, and as a result, these bacteria were transported to the neighboring beach, causing violations of state standards for swimming and shellfishing on multiple occasions during 2024, despite the beach being open for these activities. Regarding marine sites, while most water quality aspects were similar in 2024 as in 2023, *Cochlodinium* were less present this year as compared to in 2023, while *Dinophysis* were more present. *Alexandrium* was not as prevalent in 2024 as it was before 2021, though it still exceeded its respective bloom threshold on two dates in Sag Harbor Cove. However, the occurrence of harmful algal blooms and other water quality impairments affirmed the need to reduce watershed nitrogen (N) loads to improve water quality. Bacteriological measurements affirmed prior observations and provided evidence to support new conclusions. Based on studies in 2019 and 2021, enhanced spatial sampling identified marinas, surface run-off, the sewage treatment plant, and the beacon pumping stations as potential sources of pathogenic bacteria to surface waters. In 2024, fecal coliform and enterococci levels exceeded shellfishing and swimming standards, respectively, at a majority of marine sites on several occasions. Additionally, samples from storm drains throughout Sag Harbor contained elevated levels of enterococci and fecal coliform on almost every date sampled at every site.

This study has provided a refined indication of where future efforts should focus regarding both remediation and monitoring. Given the performance and capacity of the sewage treatment plant, a combination of extending sewer lines and upgrading onsite septic systems to low N systems seems warranted. The Haven’s sump is a strong source of fecal bacterial contamination to surface waters that is contaminating neighboring beaches on occasion. Fecal bacteria continue to present a problem in surface waters near the harbor. Efforts to control inputs from boats and optimal function of the sewage treatment plant is warranted. Continued monitoring of Sag Harbor surface waters is critical to assess the extent to which ongoing mitigation efforts are realized as improved water quality.

1. INTRODUCTION

Coastal marine ecosystems are amongst the most ecologically and economically productive areas on the planet, providing an estimated US\$20 trillion in annual resources or about 43% of the global ecosystem goods and services (Costanza et al., 1997). Approximately 40% of the world's population lives within 100 km of a coastline, making these regions subject to a suite of anthropogenic stressors including intense nutrient loading (Nixon, 1995; de Jonge et al., 2002; Valiela, 2006). Excessive nutrient loading into coastal ecosystems promotes algal productivity and the subsequent microbial consumption of this organic matter reduces oxygen levels and can promote hypoxia (Cloern, 2001; Heisler et al., 2008). The rapid acceleration of nutrient loading to coastal zones in recent decades has contributed to a significant expansion of algal blooms, some of which can be harmful to ecosystems or the humans who live around those ecosystems.

Globally, the phytoplankton communities of many coastal ecosystems have become increasingly dominated by harmful algal blooms (HABs) and New York's coastal waters are a prime example of this trend. Prior to 2006, algal blooms in NY were well-known for their ability to disrupt coastal ecosystem and fisheries but were never considered a human health threat. Since 2006, blooms of the saxitoxin-producing dinoflagellate *Alexandrium catenatum* have led to paralytic shellfish poisoning (PSP), inducing closures of thousands of acres of shellfish beds in Suffolk County. In 2008, a second toxic dinoflagellate, *Dinophysis acuminata*, began forming large, annual blooms that generated the toxins okadaic acid and DTX-1, both of which are the causative agents of diarrhetic shellfish poisoning (DSP).

Pathogenic bacteria are groups of microbes that also can pose a serious threat to aquatic systems and have been an increasing concern in Eastern Long Island. Such pathogens can present a hazard to humans recreating in affected waters by infecting the alimentary canal, ears, eyes, nasal cavity, skin, or upper respiratory tract, which can be exposed through immersion or the splashing of water (Thompson et al., 2005). Consumption of contaminated shellfish is one of the most common exposure routes for marine pathogens. Fecal coliform bacteria and *Enterococcus* are the recommended indicator for human pathogens in marine waters, and gastrointestinal symptoms are a frequent health outcome associated with exposure (Thompson et al., 2005). The presence of high levels of fecal coliform bacteria and/or *Enterococcus* may trigger action by a municipal agency to remediate such conditions. One key obstacle to generating a successful remediation plan for high levels of indicator bacteria such as fecal coliform bacteria and/or *Enterococcus* is that the source of the potentially pathogenic bacteria is often unknown. That is, pathogenic, fecal bacteria co-present with fecal coliform bacteria and/or *Enterococcus* may be derived from any animal, including humans and remedial plans for mitigating bacteria from human wastewater will differ radically from plans focused on the mitigation of animal feces. Moreover, mitigation of feces-derived bacteria from birds that live on the waterbody would differ radically from plans to minimize dog or deer feces that might emanate from road run-off.

During 2018 – 2023, the Gobler Laboratory performed a comprehensive study of Sag Harbor surface waters within Suffolk County to assess harmful algal bloom densities and levels of

pathogenic bacteria, in addition to measuring other water quality standards. A series of impairments (measurements below state or federal guidance values) during each summer were observed. Hypoxia (dissolved oxygen $< 3 \text{ mg L}^{-1}$) and anoxia ($< 0.5 \text{ mg L}^{-1}$) were observed in Sag Harbor Upper Cove, and, to a lesser extent, within Sag Harbor Cove and the inner harbor, from 2018-2022, though not in 2021 nor 2023. Water clarity was below the NOAA minimum for secchi disk depth (2 m) for a majority of marine sites during all years. Levels of algae (chlorophyll *a*) were above the EPA ideal value of $5 \text{ } \mu\text{g L}^{-1}$ at a majority of marine sites during all years, and at times exceeded the maximal guidance value of $20 \text{ } \mu\text{g L}^{-1}$ at various marine sites. From 2018-2020, levels of harmful algal blooms caused by *Alexandrium* and *Dinophysis* never rose to a level of concern, but high levels of the ichthyotoxic rust tide algae, *Cochlodinium*, were detected. In 2021, however, *Alexandrium*, *Dinophysis*, and *Cochlodinium* were present at all marine sites and experienced densities that exceeded their respective thresholds in which they are considered harmful to marine life. In 2022, *Cochlodinium* exceeded its threshold at least once at many marine sites, while *Dinophysis* only rose to a level of concern in Sag Harbor Cove and *Alexandrium* did not exceed its respective threshold. However, in 2023, *Alexandrium*, *Dinophysis*, and *Cochlodinium* never rose above their prospective thresholds at any sampled site. Experiments performed during all years demonstrated that nitrogen was the limiting element for the growth of algae in Sag Harbor Cove and Upper Sag Harbor Cove. Levels of fecal coliform bacteria exceeded guidance values for shellfishing on occasion during all sampled years in the inner harbor, and at Haven's Beach, with the latter location being open to shellfishing. Similarly, the levels of enterococci exceeded guidance values for swimming at several marine and Haven's beach sites during all years. From 2018-2023, the sewage treatment plant effluent site frequently exceeded the fecal coliform standard and the enterococci standard for swimming. In all sampled years, microbial source tracking revealed that sources of fecal bacteria differed by time and location and primarily included dogs and small mammals, humans, and birds. For a majority of years, the human signal was strongest within the inner harbor, while dogs and small mammals and birds were strongest for Otter Pond and Haven's Beach. Though, in 2023, dogs and small mammals made up the majority of fecal bacteria for all Haven's Beach sites and most marine sites. Lastly, nitrogen loading analyses indicated that septic tanks and cesspools were the strongest source of N for both the Cove and the Harbor, representing 70 and 90% of the total load, respectively.

Given these findings and that there are presently efforts to mitigate nitrogen loading due to septic systems, a 2024 study was undertaken to affirm some trends from the 2018 – 2023 reports. Like in previous years, the study aimed to 1.) Assess water quality across Sag Harbor and Sag Harbor Cove, 2.) Identify causes of water quality impairment, and 3.) Identify managerial actions that could be taken to improve water quality. Water quality parameters were monitored through the summer and fall of 2024 in the waters surrounding Sag Harbor. Regions covered in this study include Haven's Beach, off Amherst Road, off Notre Dame Road, off Cove Road, Sag Harbor Cove, off John Street, off Green Street, Windmill Beach and transient docks, Azurest Beach, and several storm drains in and around Sag Harbor village.

2. METHODS

2.2.1. Field sampling

The 2024 sampling season ran from 31-May-2024 through 1-October-2024, with sampling done on a bi-weekly basis. Sampling sites included three sites along Haven's Beach, eleven marine sites, and ten sites at storm drains or outfall pipes (Fig. 1).

The three sites along Haven's Beach included directly in the middle of the beach near the sump outlet within a foot of the water's edge (Haven's Beach Mid), twenty feet west of the sump outlet within a foot of the water's edge (Haven's Beach West), and twenty feet east of the sump outlet within a foot of the water's edge (Haven's Beach East). The sites along Haven's Beach were sampled for general water quality parameters (temperature, dissolved oxygen, salinity, and water clarity), chlorophyll *a* concentration, fecal coliform bacteria and Enterococcus concentrations, total nitrogen levels, and sources of microbial bacteria.

Marine sampling sites in 2024 differed from those of previous years, and new sites were introduced. Eleven marine sites were sampled in 2024, including off Amherst Road in Sag Harbor Cove, off Notre Dame Road in Sag Harbor Cove, off Cove Road in Sag Harbor Cove, off a dock at Ship Ashore Marina in Sag Harbor Cove, off John Street in Sag Harbor Cove, off Green Street in Sag Harbor Cove, north of the Long Wharf at Windmill Beach, in the middle of the Long Wharf at Windmill Beach, south of the Long Wharf at Windmill Beach, along Windmill Beach, and along Azurest Beach. These marine sites were sampled for general water quality parameters (temperature, dissolved oxygen, salinity, and water clarity), harmful algal bloom species abundances, fecal coliform bacteria and Enterococcus concentrations, chlorophyll *a* concentration, total nitrogen levels, and sources of microbial bacteria.

Lastly, samples were taken at ten storm drains and outfall pipe sites in Sag Harbor at various points in the summer. These sites included a storm drain on Amherst Road, a storm drain in the middle of Princeton Street, a big storm drain on the north side of Princeton Street, a smaller round storm drain on the south side of Princeton Street, a storm drain on the west side of Cove Road, a storm drain on the east side of Cove Road, an outfall pipe at Windmill Beach, an outfall pipe by Cormaria Retreat House, a sump pipe at Haven's Beach, and a storm drain at Azurest Beach. These sites were sampled for fecal coliform bacteria and Enterococcus concentrations, as well as total nitrogen levels. Water sampling conducted across various storm drain locations occurred in accordance with storm drain site water presence and availability of means for effective sampling procedure conduction.

At all Haven's Beach and Sag Harbor marine sites, temperature, salinity, and dissolved oxygen were measured using a YSI handheld meter at the water's surface (and at depth where applicable). Continuous measurements of temperature and dissolved oxygen were made at the Sag Harbor Cove site using a HOBO temperature/dissolved oxygen logger, which was deployed once during summer 2024. A secchi disk was used to determine water clarity. Water samples were collected with 1-L bottles, which were washed with 10% HCl, and liberally rinsed with deionized water prior to use. Once the water was collected on-site, the sampling bottle was transferred to a lab and kept in a dark, cool container (~5°C) until laboratory analyses could be performed within <6 h of collection.

2.2.2. Quantification of chlorophyll *a*

After water samples were transferred to a laboratory at Stony Brook Southampton University, 200 mL of water from each site, in triplicate, were passed through a glass fiber filter (size GFF = pore size = 0.7 μm), within a filter tower. A vacuum pump was used to drain the water through the filter tower, which was then thoroughly rinsed with 0.2 μm filtered seawater. After complete filtration, filters were removed, placed in scintillation vials, and frozen at -20°C until ready for analysis.

To analyze samples, 4 mL of 90% acetone was added to each scintillation vial and placed back in the freezer for 24 h. After 24 h, 1.5 mL of sample was extracted and placed in a 1.8 mL glass scintillation vial. These vials were then placed into a Trilogy fluorometer for final analysis. Procedures for quantifying chlorophyll *a* are based on Parsons and Strickland (1963), USEPA (1997), and Parsons (2013).

2.2.3. Quantification of harmful algal bloom species

After water samples collected from field sites were transferred to a laboratory, a whole water sample and a concentrated (1 L) water sample were preserved in acidic Lugol's iodine solution at a final concentration of 2% (v/v). To decrease the limit of detection of *Alexandrium* and *Dinophysis* in water samples, concentrated water samples were made by sieving 1 L of water through a 200 μm mesh (to eliminate large zooplankton), and then onto a 20 μm sieve and backwashed into a 15 mL centrifuge tube (Hattenrath-Lehmann et al., 2013). *Cochlodinium* counts were derived from the whole water sample. The cell densities of all harmful algal bloom species were enumerated using a 1 mL Sedgewick-Rafter slide under a compound microscope.

2.2.4. Indicator bacteria species

On each date, surface water (0.25 m depth) samples were collected in sterile 2 L bottles and transported on ice to the laboratory for further processing within two hours of collection. Triplicate whole water samples were collected for DNA analysis where samples were well-mixed, to ensure even distribution of biomass, prior to filtering 25-100 mL onto a 0.2 μm Millipore polycarbonate filter, depending on water turbidity. Samples were immediately frozen in liquid nitrogen and stored at -80°C until further processing. In parallel, sites were additionally sampled for fecal coliform bacteria and Enterococcus bacteria from June through October and quantified using the IDEXX Enterolert & Quanti-Tray/2000 sampling kits, giving MPN per 100mL. The methods for the quantification of indicator bacteria are based on standard protocols (USEPA, 1978; Eaton et al., 1998; Lipps et al., 2018).

2.2.5. Water quality standards

There are various water quality standards for marine waterbodies in New York. According to the New York State Department of Environmental Conservation (NYSDEC), levels of fecal coliform bacteria should not exceed 49 colony forming units (CFU) per 100 mL and should be, on average, below 14 CFU per 100 mL for shellfishing. According to the New York State Department of Health (NYSDOH), levels of Enterococcus should not exceed 104 CFU per 100 mL for recreational swimming. Additionally, the NYSDEC states that dissolved oxygen concentrations

are considered not conducive for aquatic life below 4.8 mg L⁻¹ and should never fall below 3.0 mg L⁻¹. The NYSDEC and the National Oceanic and Atmospheric Administration (NOAA) both state that secchi disk depth, a proxy for water clarity, should be above 2.0 m. Finally, NOAA states the maximum concentration for chlorophyll *a* should be 20 µg L⁻¹.

For harmful algal blooms, such as *Cochlodinium*, standards for what is considered a bloom vary by species. For *Cochlodinium*, the alga does not pose a threat to human health but has been shown to cause mortality in finfish and shellfish at densities at or exceeding 300 cells mL⁻¹. When mortality exceeds 300 cells mL⁻¹ in finfish and shellfish, the alga is considered to be in bloom. (Tang & Gobler, 2009).

2.2.6. Calculation of total nitrogen levels

Levels of total nitrogen were analyzed for on a Lachat Quikchem 8500 flow injection analysis system using standard wet chemistry.

2.2.7. Microbial source tracking

For 2024, microbial source tracking was utilized to assess the relative abundance of four classes of fecal bacteria at all sites in Sag Harbor. The use of digital PCR permits the quantification of bacteria specifically emanating from humans, ruminants, birds, and dogs or small mammals.

3. RESULTS

3.1. Haven's Beach

3.1.1. Discrete monitoring

During summer 2024, temperatures varied month-to-month across Haven's Beach. Temperatures at all sites ranged ~22-23°C in late May through mid-June, before increasing to ~24-25°C by late June and remaining in this range through late July (Fig. 2A). In early August through mid-August, temperatures at all sites decreased to ~22-23°C, before increasing to ~24-25°C in early September (Fig. 2A). Temperatures then decreased at all sites throughout September, to ~19°C by early October. Average surface and bottom temperatures across the Haven's Beach sites were both 23.15 ± 1.64 °C (Fig. 2B).

Salinity varied more by site across Haven's Beach in 2024. At Haven's Beach West, salinity ranged ~26-27 PSU from late May through late June (Fig. 3A). Salinity at the site then decreased to ~24 PSU in early July, increased to ~28 PSU by the end of July through early August, decreased to ~26 PSU by late August, decreased further to ~22 PSU by early September, and finally increased to ~28-29 PSU in mid-September through early October (Fig. 3A). Meanwhile, at Haven's Beach Mid, salinity increased from ~24 PSU in late May to ~26-27 PSU in early June through late June, decreased to ~25 PSU by early July, decreased further to ~13 PSU by late July, increased to ~27-28 PSU by early August through late August, decreased to ~26 PSU by early September, and finally increased to ~28-29 PSU by mid-September through early October (Fig. 3A). Finally, at Haven's Beach East, salinity remained ~26-27 PSU from late May through early July, before increasing to ~28 PSU by late July through late August (Fig. 3A). Salinity at the site then decreased to ~26 PSU in early September, increased to ~28 PSU by mid-September, and

decreased to ~26 PSU by early October (Fig. 3A). Average surface and bottom salinities across the Haven's Beach sites were both 26.21 ± 2.31 PSU (Fig. 3B).

Dissolved oxygen concentrations at Haven's Beach in summer 2024 exceeded the NYSDEC DO minimum (4.8 mg L^{-1}) during every month (Fig. 4A). Dissolved oxygen decreased at all sites from ~9-10 mg L^{-1} in early May to ~8-9 mg L^{-1} by mid-June through early July, before decreasing again to ~7-8 mg L^{-1} by late July through early September (Fig. 4A). At that point, dissolved oxygen at all sites increased to ~8-9 mg L^{-1} in mid-August through the remainder of the season (Fig. 4A). During summer, the average surface and bottom DO concentrations were $8.25 \pm 0.23 \text{ mg L}^{-1}$ and $8.35 \pm 0.19 \text{ mg L}^{-1}$, respectively, both exceeding the NYSDEC DO minimum (Fig. 4B).

Chlorophyll *a* concentration across Haven's Beach fluctuated drastically throughout the summer months of 2024, exceeding the EPA ideal value of $5 \text{ } \mu\text{g L}^{-1}$ for a majority of the summer, but never exceeding the maximal guidance value of $20 \text{ } \mu\text{g L}^{-1}$ (Fig. 5A). At Haven's Beach West, chlorophyll *a* decreased from ~7 $\text{ } \mu\text{g L}^{-1}$ at the end of May to ~4 $\text{ } \mu\text{g L}^{-1}$ in mid-June, increased to ~10 $\text{ } \mu\text{g L}^{-1}$ by early July, increased further to ~18 $\text{ } \mu\text{g L}^{-1}$ by the end of July, decreased to ~7 $\text{ } \mu\text{g L}^{-1}$ in the middle of August, rose again to ~8 $\text{ } \mu\text{g L}^{-1}$ by the beginning of September, and finally fell to ~4 $\text{ } \mu\text{g L}^{-1}$ in mid-September (Fig. 5A). At Haven's Beach Mid, chlorophyll *a* decreased from ~6 $\text{ } \mu\text{g L}^{-1}$ at the end of May to ~4 $\text{ } \mu\text{g L}^{-1}$ in mid-June, increased to ~8 $\text{ } \mu\text{g L}^{-1}$ by early July, increased further to ~14 $\text{ } \mu\text{g L}^{-1}$ by the end of July, decreased to ~9 $\text{ } \mu\text{g L}^{-1}$ in the middle of August, and continued to decrease to ~6-7 $\text{ } \mu\text{g L}^{-1}$ by late August and to ~5 $\text{ } \mu\text{g L}^{-1}$ by mid-September (Fig. 5A). Meanwhile, at Haven's Beach East, chlorophyll *a* decreased from ~4 $\text{ } \mu\text{g L}^{-1}$ at the end of May to ~3 $\text{ } \mu\text{g L}^{-1}$ in late June, increased to ~5 $\text{ } \mu\text{g L}^{-1}$ by early July, increased further to ~16 $\text{ } \mu\text{g L}^{-1}$ by the end of July, decreased to ~6-7 $\text{ } \mu\text{g L}^{-1}$ in the middle of August, rose again to ~11 $\text{ } \mu\text{g L}^{-1}$ by the beginning of September, and finally fell to ~4 $\text{ } \mu\text{g L}^{-1}$ in mid-September (Fig. 5A). For the summer, total chlorophyll *a* concentration at the Haven's Beach West, Haven's Beach Mid, and Haven's Beach East sites were, on average, $7.43 \pm 1.40 \text{ } \mu\text{g L}^{-1}$, $6.95 \pm 0.96 \text{ } \mu\text{g L}^{-1}$ and $6.80 \pm 1.35 \text{ } \mu\text{g L}^{-1}$, respectively, with maximum concentrations of $17.65 \text{ } \mu\text{g L}^{-1}$, $13.77 \text{ } \mu\text{g L}^{-1}$ and $16.42 \text{ } \mu\text{g L}^{-1}$, respectively (Fig. 5B). The average and maximum chlorophyll *a* concentration exceeded the EPA ideal value at all sites, though did not exceed the USEPA chlorophyll *a* maximum (Fig. 5B).

Secchi disk depth was 0.5 m for all Haven's Beach sites through the entirety of summer, remaining below the NOAA secchi disk minimum (2 m). However, sampling at these sites occurred in shallow water.

3.1.2. Indicator bacteria

Fecal coliform bacteria levels exceeded the NYSDEC fecal coliform standard for shellfish (14 CFU per 100 mL) at Haven's Beach West on four dates in summer 2024 (23-July-2024, 8-August-2024, 17-September 2024, and 1-October-2024) when levels were ~86 CFU per 100 mL, 27 CFU per 100 mL, 15 CFU per 100 mL, and 71 CFU per 100 mL, respectively (Fig. 6A). At Haven's Beach East, fecal coliform levels exceeded the NYSDEC fecal coliform standard for shellfish on 23-July-2024, 8-August-2024, and 1-October-2024, when levels were ~57 CFU per 100 mL, ~333 CFU per 100 mL, and ~63 CFU per 100 mL, respectively (Fig. 6A). Finally, fecal coliform bacteria levels exceeded the NYSDEC fecal coliform standard for

shellfish at Haven's Beach East on five dates in summer 2024 (9-July-2024, 23-July-2024, 8-August-2024, 17-September 2024, and 1-October-2024) when levels were ~50 CFU per 100 mL, ~47 CFU per 100 mL, ~32 CFU per 100 mL, ~24 CFU per 100 mL, and ~83 CFU per 100 mL respectively (Fig. 6A). On all other dates, fecal coliform bacteria levels never rose above ~10 CFU per 100 mL at any site (Fig. 6A).

At Haven's Beach West, enterococci levels exceeded the NYSDEC enterococci standard for swimming (104 CFU per 100 mL) on four dates in summer 2024 (9-July-2024, 23-July-2024, 4-September-2024, and 1-October 2024), when levels were >401 CFU per 100 mL for the first three dates, and ~300 CFU per 100 mL on 1-October-2024 (Fig. 6B). On all other dates, enterococci levels ranged ~14-94 CFU per 100 mL at the site. Enterococci levels at Haven's Beach Mid exceeded the NYSDEC enterococci standard for swimming on 9-July-2024, 23-July-2024, and 1-October-2024, when levels were ~176 CFU per 100 mL, >401 CFU per 100 mL, and >401 CFU per 100 mL, respectively (Fig. 6B). On all other dates, enterococci levels ranged ~6-62 CFU per 100 mL at the site (Fig. 6B). Finally, at Haven's Beach East enterococci levels exceeded the NYSDEC enterococci standard for swimming on four dates in summer 2024 (9-July-2024, 23-July-2024, 17-September-2024, and 1-October 2024), when levels were ~372 CFU per 100 mL, >401 CFU per 100 mL, ~111 CFU per 100 mL, and >401 CFU per 100 mL, respectively (Fig. 6B). On all other dates at the site, enterococci levels ranged ~4-53 CFU per 100 mL (Fig. 6B).

3.1.3 Total nitrogen levels

Total nitrogen levels were found at Haven's Beach Mid, but not at Haven's Beach West nor Haven's Beach East (Fig. 7). At Haven's Beach Mid, total nitrogen levels increased from ~0.39 mg N/L in late May, to ~0.41 mg N/L in late June, and then to ~0.48 mg N/L by late July (Fig. 7). At that point, total nitrogen at the site decreased to ~0.42 mg N/L by late August, before decreasing again to ~29 mg N/L by mid-September, and to ~26 mg N/L by early October (Fig. 7).

3.1.4 Microbial Source Tracking

At Haven's Beach West, fecal bacteria abundances increased from ~696 genomic copies per 100 mL in late June to ~723 genomic copies per 100 mL in late August, before decreasing to ~352 genomic copies per 100 mL in early October (Fig. 8A). Fecal bacteria abundances at Haven's Beach Mid followed a similar pattern, increasing from ~514 genomic copies per 100 mL in late June to ~617 genomic copies per 100 mL in late August, and then decreasing to ~220 genomic copies per 100 mL by the beginning of October (Fig. 8A). At Haven's Beach East fecal bacteria abundance decreased from ~588 genomic copies per 100 mL in late June to ~411 genomic copies per 100 mL in late August, before increasing to ~452 genomic copies per 100 mL by early October (Fig. 8A). On average, fecal bacteria abundance at Haven's Beach West, Haven's Beach Mid, and Haven's Beach East in summer 2024 were ~591 genomic copies per 100 mL, ~450 genomic copies per 100 mL, and ~483 genomic copies per 100 mL, respectively (Fig. 8B). At all Haven's Beach sites, dogs and small mammals made up the largest percentage of fecal bacteria (~87-94%), while fecal bacteria from birds made up ~5-9% (Fig. 8C). Humans and ruminants made up <2% of fecal bacteria at any site (Fig. 8C).

From late June to late August, enterococcus abundances increased from ~411 genomic copies per 100 mL to ~1867 genomic copies per 100 mL at Haven's Beach West, from ~596 genomic copies per 100 mL to ~2456 genomic copies per 100 mL at Haven's Beach Mid, and from ~744 genomic copies per 100 mL to ~3538 genomic copies per 100 mL at Haven's Beach East (Fig. 9A). By the beginning of October, enterococcus abundance then decreased at Haven's Beach West, Haven's Beach Mid, and Haven's Beach East to ~1470 genomic copies per 100 mL, ~145 genomic copies per 100 mL, and ~1719 genomic copies per 100 mL, respectively (Fig. 9A). Average enterococcus abundance at Haven's Beach West, Haven's Beach Mid, and Haven's Beach East were ~1249 genomic copies per 100 mL, ~1066 genomic copies per 100 mL, and ~2000 genomic copies per 100 mL, respectively (Fig. 9B).

3.2. Marine sites

3.2.1. Discrete monitoring

During 2024, temperature was relatively consistent across the Sag Harbor marine sites. Only at Amherst Beach were temperatures a bit higher when compared to the other marine sites (Fig. 10A). At Amherst Beach, temperatures increased from ~24°C in late May to ~27-28°C by mid-June, remained ~27-28°C through the end of June and throughout July, before decreasing to ~24-25°C by the beginning of August into September, and to ~20°C by early October (Fig. 10A). At all other sites, temperature increased from ~20-23°C in late May through mid-June to ~24-27°C in by late June, remained ~24-27°C throughout July, decreased to ~23-25°C at the start of August and into September, and finally decreased to ~19-20°C by the end of September and into October, though measurements at Notre Dame, John Street, Green Street, and Azurest Beach were only made starting 21-August-2024 (Fig. 10A). Average surface and bottom temperatures across the marine sites were $23.27 \pm 1.97^\circ\text{C}$ and $23.17 \pm 1.95^\circ\text{C}$, respectively (Fig. 10B). Continuous measurements of temperature at the Sag Harbor Cove site showed that temperatures fluctuated greatly from 25-June-2024 through 1-July-2024, ranging between ~17°C and ~29°C. From 1-July-2024 through 2-July-2024, temperature increased from ~19°C to ~24°C, before steadying to ~25-28°C from 3-July-2024 through 5-August-2024 (Fig. 11). Temperatures then decreased from ~28°C on 5-August-2024 to ~23°C by 9-August-2024, before increasing to ~25°C by 10-August-2024 and remaining ~24-25°C until sampling ended on 19-August-2024 (Fig. 11).

At Amherst Road, Notre Dame, Cove Road, Sag Harbor Cove, John Street, Green Street, Long Wharf North, Long Wharf Mid, Long Wharf South, Windmill Beach, and Azurest Beach, salinity ranged ~23.1-28.2 PSU, ~10.5-28.1 PSU, ~24.1-28.8 PSU ~25.3-28.8 PSU, ~20.9-26.7 PSU, ~23.9-27.7 PSU, ~26.1-29.2 PSU, ~25.8-29.2 PSU, ~26.6-29.3 PSU, ~24.5-29.0 PSU, and ~22.2-27.8 PSU, respectively, though measurements at Notre Dame, John Street, Green Street, and Azurest Beach were only made starting 21-August-2024 (Fig. 12A). Average surface and bottom salinities across the marine sites were 26.16 ± 2.04 PSU and 26.27 ± 1.95 PSU, respectively (Fig. 12B).

During 2024, dissolved oxygen concentrations at Amherst Road, Notre Dame, Sag Harbor Cove, John Street, Green Street, Long Wharf North, Long Wharf Mid, Long Wharf South, Windmill Beach, and Azurest Beach ranged ~5.5-9.0 mg L⁻¹, ~5.7-8.9 mg L⁻¹, ~5.3-7.7 mg L⁻¹, ~7.5-9.1 mg L⁻¹, ~4.9-10.5 mg L⁻¹, ~5.4-7.6 mg L⁻¹, ~5.7-7.4 mg L⁻¹, ~5.5-8.0 mg L⁻¹,

~5.9-8.0 mg L⁻¹, and ~8.9-9.8 mg L⁻¹, respectively, never falling below the NYSDEC DO minimum (4.8 mg L⁻¹) (Fig. 13A). Though measurements at Notre Dame, John Street, Green Street, and Azurest Beach were only made starting 21-August-2024 (Fig. 13A). At Cove Road, DO concentrations fell below the NYSDEC DO minimum to ~4.5 mg L⁻¹ on one date (23-July-2024) (Fig. 13A). On all other dates, DO concentrations at the site ranged ~6.2-9.8 mg L⁻¹ (Fig. 13A). Average surface and bottom DO concentrations across the Sag Harbor marine sites were 7.59 ± 0.98 mg L⁻¹ and 7.51 ± 0.99 mg L⁻¹, respectively, which were both above the NYSDEC DO minimum (Fig. 13B). Continuous measurements of dissolved oxygen at the Sag Harbor Cove site showed that DO concentrations remained between ~5-10 mg L⁻¹ for a majority of the time between 26-June-2024 and 12-August-2024, with the exception of four instances where DO concentrations fell below ~4 mg L⁻¹ (3-July-2024, 6-July-2024 through 8-July-2024, 14-July-2024 through 15-July-2024, and 31-July-2024), which is below the NYSDEC DO minimum (Fig. 14). From 19-July-2024 through 22-July-2024 and from 7-August-2024 through 12-August-2024, it is thought the DO logger at Sag Harbor Cove malfunctioned, so no data is reported for those time ranges (Fig. 14). DO concentrations at the site then decreased from ~11 mg L⁻¹ on 13-August-2024 to ~6 mg L⁻¹ by 19-August-2024 (Fig. 14).

Secchi disk depths at Amherst Road, Notre Dame, Cove Road, John Street, Green Street, and Windmill Beach were consistently 0.5 m for the entirety of summer 2024, remaining below the NOAA secchi disk minimum (2 m). However, these sites were sampled in shallow water. Secchi disk depths at Sag Harbor Cove also remained below the NOAA secchi disk minimum during summer 2024 (Fig. 15). At Sag Harbor Cove, secchi disk depth increased from 1.5 m in late May to 1.7 m in mid-June, before decreasing through July and August to 0.6 m by the end of August (Fig. 15). Secchi disk depths at the site then increased to 1.1 m by early September, increased again to 1.8 m by mid-September and finally decreased to 1.5 by early October (Fig. 15). At all Long Wharf sites, secchi disk depth ranged 1.5-2 m from late May through late June, decreased to 1.1-1.6 m from early July through late August, and then increased to 1.5-2 m in early September (Fig. 15). At that point, secchi disk depth at Long Wharf North increased to 1.8 m in mid-September, before decreasing to 1.5 m in early October (Fig. 15). Meanwhile, at Long Wharf Mid and Long Wharf South, secchi disk depth increased throughout the remainder of the summer to 2.5 m and 2.8 m, respectively, exceeding the NOAA secchi disk minimum at both sites (Fig. 15).

Chlorophyll *a* concentration across the Sag Harbor marine sites varied greatly in 2024. At Amherst Road, chlorophyll *a* concentration exceeded the USEPA chlorophyll *a* maximum (20 µg L⁻¹) on 4-September-2024 when concentration peaked at ~26.3 µg L⁻¹ (Fig. 16A). On all other dates, chlorophyll *a* concentration at the site ranged ~2.8-15.7 µg L⁻¹ (Fig. 16A). At Notre Dame, Cove Road, Sag Harbor Cove, and Windmill Beach, chlorophyll *a* concentration ranged ~5.1-10.9 µg L⁻¹, ~0.9-8.4 µg L⁻¹, ~2.5-18.0 µg L⁻¹, and ~2.9-5.7 µg L⁻¹, respectively, never exceeding the USEPA maximum (Fig. 16A). At John Street, chlorophyll *a* concentration exceeded the USEPA chlorophyll *a* maximum on 8-August-2024 when concentration peaked at ~20.1 µg L⁻¹ (Fig. 16A). On all other dates, chlorophyll *a* concentration at the site ranged ~12.2-13.7 µg L⁻¹ (Fig. 16A). Similarly, chlorophyll *a* concentration at Green Street exceeded the USEPA chlorophyll *a* maximum only once during summer 2024, on 21-August-2024, when concentration peaked at ~24.7 µg L⁻¹ (Fig. 16A). On all other dates, chlorophyll *a* concentration at the site ranged ~7.3-

12.1 $\mu\text{g L}^{-1}$ (Fig. 16A). Chlorophyll *a* concentrations were not measured at Long Wharf Mid, Long Wharf North, Long Wharf South, nor Azurest Beach in 2024 (Fig. 16A). Chlorophyll measurements at Notre Dame, John Street, and Green Street, were only made starting 21-August-2024 (Fig. 16A). Average summer chlorophyll *a* concentration across Amherst Road, Notre Dame, Cove Road, Sag Harbor Cove, John Street, Green Street and Windmill Beach were $10.76 \pm 7.28 \mu\text{g L}^{-1}$, $7.31 \pm 2.24 \mu\text{g L}^{-1}$, $4.10 \pm 2.01 \mu\text{g L}^{-1}$, $6.92 \pm 4.43 \mu\text{g L}^{-1}$, $15.35 \pm 3.40 \mu\text{g L}^{-1}$, $13.87 \pm 6.53 \mu\text{g L}^{-1}$, and $4.09 \pm 0.98 \mu\text{g L}^{-1}$, respectively, which are all below the USEPA chlorophyll *a* maximum (Fig. 16B). Though, the average summer chlorophyll at Cove Road and Windmill Beach are below the EPA ideal value of $5 \mu\text{g L}^{-1}$ (Fig. 16B). Maximum summer chlorophyll *a* concentration across Amherst Road, Notre Dame, Cove Road, Sag Harbor Cove, John Street, Green Street and Windmill Beach were $26.29 \mu\text{g L}^{-1}$, $10.91 \mu\text{g L}^{-1}$, $8.36 \mu\text{g L}^{-1}$, $18.04 \mu\text{g L}^{-1}$, $20.07 \mu\text{g L}^{-1}$, $11.37 \mu\text{g L}^{-1}$, and $5.77 \mu\text{g L}^{-1}$, respectively (Fig. 16B).

3.2.2. Harmful algal bloom species

In 2024, the densities of harmful algal bloom species (*Cochlodinium* and *Dinophysis*) were found at Amherst Road, Cove Road, Sag Harbor Cove, and Windmill Beach. All other marine sites (Notre Dame, John Street, Green Street, Long Wharf North, Long Wharf South, and Azurest Beach) were not sampled for harmful algal bloom densities.

Cochlodinium densities did not exceed their respective bloom threshold ($300 \text{ cells mL}^{-1}$) at any site during any date in summer 2024 (Fig. 17A). At Amherst Road, densities of *Cochlodinium* ranged ~ 0 - $2.5 \text{ cells mL}^{-1}$ across all dates (Fig. 17A). At Cove Road, *Cochlodinium* densities were 0 cells mL^{-1} except on 21-August-2024 and 4-September-2024, when densities were 2 cells mL^{-1} and 6 cells mL^{-1} , respectively (Fig. 17A). At Sag Harbor Cove, *Cochlodinium* densities were 0 cells mL^{-1} except on 26-August-2024 and 23-September-2024, when densities were $100 \text{ cells mL}^{-1}$ and $4.5 \text{ cells mL}^{-1}$, respectively (Fig. 17A). At Windmill Beach, *Cochlodinium* was only present on one date (4-September-2024) when density was 2 cells mL^{-1} (Fig. 17A).

In contrast, the presence of *Dinophysis* was greater in 2024, though did not exceed its respective bloom threshold ($10,000 \text{ cells mL}^{-1}$) at any site during date (Fig. 17B). At Amherst Road, *Dinophysis* concentration increased from $175 \text{ cells mL}^{-1}$ in late May to $250 \text{ cells mL}^{-1}$ by mid-June, before decreasing to $112 \text{ cells mL}^{-1}$ by late June, and again to 0 - 1 cells mL^{-1} for the remainder of the summer (Fig. 17B). At Cove Road, *Dinophysis* concentration decreased from $3150 \text{ cells mL}^{-1}$ in late May to $700 \text{ cells mL}^{-1}$ in mid-June, increased to $6475 \text{ cells mL}^{-1}$ in late June and then decreased to 0 cells mL^{-1} for the remainder of the summer. *Dinophysis* concentration at Sag Harbor Cove ranged ~ 0 - $6475 \text{ cells mL}^{-1}$ across all dates with the peak occurring in late May (Fig. 17B). Finally, at Windmill Beach, *Dinophysis* was found on only one date (25-June-2024), at a density of $112 \text{ cells mL}^{-1}$ (Fig. 17B).

Alexandrium was not present at Amherst Road, Cove Road, nor Windmill Beach on any date in 2024 (Fig. 17C). Densities of *Alexandrium* at Sag Harbor Cove ranged ~ 117 - $6125 \text{ cells mL}^{-1}$ between mid-April to mid-May and exceeded its respective bloom threshold ($1000 \text{ cells mL}^{-1}$) on 29-April-2024 and 13-May-2024 when densities were $1108 \text{ cells mL}^{-1}$ and $6125 \text{ cells mL}^{-1}$, respectively (Fig. 17C). On all other dates samples, *Alexandrium* density was 0 cells mL^{-1} at the site (Fig. 17C).

3.2.3. Indicator bacteria

At Amherst Road, fecal coliform levels exceeded the NYSDEC fecal coliform standard for shellfish on six of the eight dates sampled (31-May-2024, 11-June-2024, 25-June-2024, 8-August-2024, 21-August-2024, and 1-October-2024), when levels were ~143 CFU per 100 mL, 22 CFU per 100 mL, ~63 CFU per 100 mL, ~20 CFU per 100 mL, ~237 CFU per 100 mL, and ~24 CFU per 100 mL, respectively (Fig. 18A). On all other dates, fecal coliform levels ranged ~2-10 CFU per 100 mL. At Notre Dame fecal coliform levels exceeded the NYSDEC fecal coliform standard for shellfish on 21-August-2024 and 17-September-2024 when levels were ~22 CFU per 100 mL and ~65 CFU per 100 mL, respectively (Fig. 18A). Fecal coliform levels at Cove Road exceeded the NYSDEC fecal coliform standard for shellfish in four of the eight dates sampled (31-May-2024, 23-July-2024, 8-August-2024, and 1-October 2024), when levels were ~391 CFU per 100 mL, >401 CFU per 100 mL, ~108 CFU per 100 mL, and ~15 CFU per 100 mL, respectively (Fig. 18A). On all other dates, fecal coliform levels ranged ~2-8 CFU per 100 mL at this site (Fig. 18A). At Sag Harbor Cove, fecal coliform levels exceeded the NYSDEC fecal coliform standard for shellfish in three of the eight dates sampled (8-August-2024, 17-September-2024, and 1-October-2024), when levels were ~35 CFU per 100 mL, 15 CFU per 100 mL, and ~19 CFU per 100 mL (Fig. 18A). On all other dates, fecal coliform levels ranged ~1-8 CFU per 100 mL at the site (Fig. 18A). Fecal coliform levels at John Street ranged ~29-247 CFU per 100 mL, exceeding the NYSDEC fecal coliform standard for shellfish on all four dates the site was sampled (Fig. 18A). At Green Street, fecal coliform levels exceeded the NYSDEC fecal coliform standard for shellfish on 21-August-2024 and 1-October-2024, when levels were ~29 CFU per 100 mL and ~60 CFU per 100 mL, respectively (Fig. 18A). On all other dates, fecal coliform levels ranged ~8-10 CFU per 100 mL at the site (Fig. 18A). Fecal coliform levels at Windmill Beach exceeded the NYSDEC fecal coliform standard for shellfish on all dates the site was sampled and ranged ~32-255 CFU per 100 mL (Fig. 18A). Finally, at Azurest Beach fecal coliform levels exceeded the NYSDEC fecal coliform standard for shellfish on 4-September-2024 and 1-October-2024, when levels were ~123 CFU per 100 mL and ~20 CFU per 100 mL, respectively (Fig. 18A). On all other dates, fecal coliform levels did not exceed 2 CFU per 100 mL at this site (Fig. 18A).

At Amherst Road enterococci levels exceeded the NYSDEC enterococci standard for swimming (104 CFU per 100 mL) on six of the eight dates sampled (25-June-2024, 9-July-2024, 23-July-2024, 21-August-2024, 4-September-2024, and 17-September-2024), when levels were >401 CFU per 100 mL, >401 CFU per 100 mL, ~129 CFU per 100 mL, ~271 CFU per 100 mL, ~356 CFU per 100 mL, and >401 CFU per 100 mL, respectively (Fig. 18B). On all other dates, enterococci levels ranged ~46-64 CFU per 100 mL at the site (Fig. 18B). At Notre Dame, enterococci levels exceeded the NYSDEC enterococci standard for swimming on three dates in summer 2024 (4-September-2024, 17-September-2024, and 1-October-2024), when levels were ~147 CFU per 100 mL, ~229 CFU per 100 mL, and ~271 CFU per 100 mL, respectively (Fig. 18B). On the only other date sampled at Notre Dame, enterococci levels were ~85 CFU per 100 mL (Fig. 18B). Enterococci levels only exceeded NYSDEC enterococci standard for swimming at Cove Road on 9-July-2024 when levels were >401 CFU per 100 mL (Fig. 18B). On all other dates sampled, enterococci levels ranged ~14-91 CFU per 100 mL at the site (Fig. 18B). Similarly at

Sag Harbor Cove, enterococci levels exceeded NYSDEC enterococci standard for swimming only once during summer 2024, on 25-June-2024 when levels were >401 CFU per 100 mL (Fig. 18B). On all other dates, enterococci levels ranged ~2-95 CFU per 100 mL at the site (Fig. 18B). At John Street, enterococci levels exceeded the NYSDEC enterococci standard for swimming on three dates of four dates sampled (21-August-2024, 4-September-2024, and 17-September-2024) when levels were >401 CFU per 100 mL on all three dates (Fig. 18B). On the only other date sampled at John Street, enterococci levels were ~79 CFU per 100 mL (Fig. 18B). Enterococci levels at Green Street exceeded the NYSDEC enterococci standard for swimming on all dates the site was sampled and ranged ~151-<401 CFU per 100 mL (Fig. 18B). At Windmill Beach, enterococci levels exceeded the NYSDEC enterococci standard for swimming on five of the eight dates sampled (31-May-2024, 11-June-2024, 9-July-2024, 17-September-2024, and 1-October-2024), when levels were ~335 CFU per 100 mL, ~171 CFU per 100 mL, >401 CFU per 100 mL, >401 CFU per 100 mL, and >401 CFU per 100 mL, respectively (Fig. 18B). On all other dates, fecal enterococci levels ranged ~29-93 CFU per 100 mL (Fig. 18B). Finally, enterococci levels at Azurest Beach exceeded the NYSDEC enterococci standard for swimming on 4-September-2024 and 17-September-2024 when levels were >401 CFU per 100 mL on both dates (Fig. 18B). On all other dates, enterococci levels ranged ~57-73 CFU per 100 mL at the site (Fig. 18B).

3.2.4. Total nitrogen levels

Total nitrogen levels at Amherst Road, Notre Dame, Cove Road, Sag Harbor Cove, John Street, Green Street, Windmill Beach, and Azurest Beach ranged ~0.38-0.55 mg N/L, ~0.37-0.73 mg N/L, ~0.27-0.48 mg N/L, ~0.24-0.53 mg N/L, ~0.33-0.98 mg N/L, ~0.27-0.67 mg N/L, ~0.28-0.73 mg N/L, and ~0.14-1.81 mg N/L, respectively (Fig. 19A). Average summer total nitrogen levels were $\sim 0.47 \pm 0.06$ mg N/L, $\sim 0.53 \pm 0.13$ mg N/L, $\sim 0.41 \pm 0.08$ mg N/L, $\sim 0.40 \pm 0.09$ mg N/L, $\sim 0.72 \pm 0.22$ mg N/L, $\sim 0.51 \pm 0.15$ mg N/L, $\sim 0.43 \pm 0.15$ mg N/L, and $\sim 0.64 \pm 0.61$ mg N/L, at Amherst Road, Notre Dame, Cove Road, Sag Harbor Cove, John Street, Green Street, Windmill Beach, and Azurest Beach, respectively (Fig. 19B).

Long Wharf sites (Long Wharf South, Long Wharf Mid, and Long Wharf North) were not sampled for total nitrogen levels in summer 2024. Total nitrogen levels at Notre Dame, John Street, Green Street, and Azurest Beach were only found starting 8-August-2024 (Fig. 19A).

3.2.5. Microbial Source Tracking

At Amherst Road, fecal bacteria abundances decreased from ~692 genomic copies per 100 mL in late August to ~344 genomic copies per 100 mL in early October (Fig. 20A). Fecal bacteria abundance was only sampled once during summer 2024 (1-October-2024) at Notre Dame, John Street, Green Street, and Azurest Beach, where abundances were ~384 genomic copies per 100 mL, 240 genomic copies per 100 mL, 96 genomic copies per 100 mL, and ~1057 genomic copies per 100 mL, respectively (Fig. 20A). At Cove Road, fecal bacteria abundances decreased from ~3332 genomic copies per 100 mL in late August to ~1416 genomic copies per 100 mL in early October (Fig. 20A). Fecal bacteria abundance at Sag Harbor Cove decreased from ~538 genomic copies per 100 mL in late June to ~50 genomic copies per 100 mL by late August, before increasing to ~116 genomic copies per 100 mL in early October (Fig. 20A). At

Long Wharf North, fecal bacteria abundances increased from ~167 genomic copies per 100 mL in late June to ~259 genomic copies per 100 mL in late August and increased again to ~883 genomic copies per 100 mL by early October (Fig. 20A). Meanwhile at Long Wharf Mid, fecal bacteria abundances decreased from ~600 genomic copies per 100 mL in late June to ~259 genomic copies per 100 mL in late August, before increasing to ~883 genomic copies per 100 mL in early October (Fig. 20A). Fecal bacteria abundances at Long Wharf South increased from ~310 genomic copies per 100 mL in late June to ~2500 genomic copies per 100 mL in late August, before decreasing to ~1769 genomic copies per 100 mL in early October (Fig. 20A). Finally, at Windmill Beach fecal bacteria abundances increased from ~322 genomic copies per 100 mL in late June to ~1743 genomic copies per 100 mL in late August and increased again to ~2044 genomic copies per 100 mL by early October (Fig. 20A). On average, fecal bacteria abundance at Amherst Road, Notre Dame, Cove Road, Sag Harbor Cove, John Street, Green Street, Long Wharf North, Long Wharf Mid, Long Wharf South, Windmill Beach, and Azurest Beach in summer 2024 were ~518 genomic copies per 100 mL, ~384 genomic copies per 100 mL, ~2374 genomic copies per 100 mL, ~430 genomic copies per 100 mL, 240 genomic copies per 100 mL, 96 genomic copies per 100 mL, ~1270 genomic copies per 100 mL, ~131 genomic copies per 100 mL, ~581 genomic copies per 100 mL, ~1551 genomic copies per 100 mL, and ~1057 genomic copies per 100 mL, respectively (Fig. 20B). For all Sag Harbor Marine sites excluding Notre Dame, dogs and small mammals made up the largest percentage of fecal bacteria (~53-88%), followed by birds (~8-36%) (Fig. 20C). At Notre Dame, birds made up the largest percentage of fecal bacteria (~70%). Humans and ruminants made up <13% of fecal bacteria at any site (Fig. 20C).

From late August to early October, enterococcus abundances at Amherst Road increased from ~695 genomic copies per 100 mL to ~730 genomic copies per 100 mL (Fig. 21A). Enterococcus abundance was only sampled once during summer 2024 (1-October-2024) at Notre Dame, John Street, Green Street, and Azurest Beach, where abundances were ~2121 genomic copies per 100 mL, ~2431 genomic copies per 100 mL, ~1132 genomic copies per 100 mL, and ~1056 genomic copies per 100 mL, respectively (Fig. 21A). At Cove Road, enterococcus abundances increased from ~1309 genomic copies per 100 mL in late August to ~2656 genomic copies per 100 mL in early October (Fig. 21A). Enterococcus abundance at Sag Harbor Cove decreased from ~1481 genomic copies per 100 mL in late June to ~200 genomic copies per 100 mL by late August, before increasing to ~275 genomic copies per 100 mL in early October (Fig. 21A). At Long Wharf North, enterococcus abundances increased from ~407 genomic copies per 100 mL in late June to ~1076 genomic copies per 100 mL in late August and increased again to ~2930 genomic copies per 100 mL by early October (Fig. 21A). Meanwhile at Long Wharf Mid, enterococcus abundances increased from ~453 genomic copies per 100 mL in late June to ~1239 genomic copies per 100 mL in late August, before decreasing to ~1154 genomic copies per 100 mL in early October (Fig. 21A). Enterococcus abundances at Long Wharf South increased from ~1382 genomic copies per 100 mL in late June to ~1675 genomic copies per 100 mL in late August, before decreasing to ~1590 genomic copies per 100 mL in early October (Fig. 21A). Finally, at Windmill Beach enterococcus abundances increased from ~1280 genomic copies per 100 mL in late June to ~2799 genomic copies per 100 mL in late August and increased again to ~7500 genomic copies per 100 mL by early October (Fig. 21A). On average, enterococcus

abundance at Amherst Road, Notre Dame, Cove Road, Sag Harbor Cove, John Street, Green Street, Long Wharf North, Long Wharf Mid, Long Wharf South, Windmill Beach, and Azurest Beach in summer 2024 were ~713 genomic copies per 100 mL, ~2121 genomic copies per 100 mL, ~1982 genomic copies per 100 mL, ~846 genomic copies per 100 mL, ~2431 genomic copies per 100 mL, ~1132 genomic copies per 100 mL, ~1471 genomic copies per 100 mL, ~770 genomic copies per 100 mL, ~949 genomic copies per 100 mL, ~4278 genomic copies per 100 mL, and ~1056 genomic copies per 100 mL, respectively (Fig. 21B).

3.3 Storm Drains

3.3.1. Indicator bacteria

Fecal coliform levels at the Amherst Road storm drain, Princeston Street North storm drain, Cove Road storm drain, Windmill Beach outfall pipe, Cormaria outfall pipe, Haven's Beach Sump Pipe and Azurest Beach storm drain ranged ~232-2920 CFU per 100 mL, ~14-3972 CFU per 100 mL, ~10-4839 CFU per 100 mL, ~24-977 CFU per 100 mL, ~186-1095 CFU per 100 mL, ~15-615 CFU per 100 mL, and ~374-3973 CFU per 100 mL, respectively (Fig. 22A). At Princeston Street Big storm drain, Princeston Street Round storm drain, Cove Road West storm drain, and Union Street storm drain fecal coliform levels were only sampled once when levels were ~630 CFU per 100 mL, ~110 CFU per 100 mL, ~49 CFU per 100 mL, and ~192 CFU per 100 mL, respectively (Fig. 22A). Average fecal coliform levels for the summer at the Amherst Road storm drain, Princeston Street North storm drain, Cove Road storm drain, Windmill Beach outfall pipe, Cormaria outfall pipe, Haven's Beach Sump Pipe and Azurest Beach storm drain during the summer were ~967 CFU per 100 mL, ~1915 CFU per 100 mL, ~1348 CFU per 100 mL, ~348 CFU per 100 mL, ~772 CFU per 100 mL, ~162 CFU per 100 mL, and ~2174 CFU per 100 mL, respectively (Fig. 22B).

Enterococci levels at the Amherst Road storm drain, Princeston Street North storm drain, Cove Road storm drain, Windmill Beach outfall pipe, Cormaria outfall pipe, Haven's Beach Sump Pipe and Azurest Beach storm drain ranged ~63-908 CFU per 100 mL, ~132-4839 CFU per 100 mL, ~292-4839 CFU per 100 mL, ~182-2407 CFU per 100 mL, ~1454-1961 CFU per 100 mL, ~24-4839 CFU per 100 mL, and ~1540-2827 CFU per 100 mL, respectively (Fig. 23A). At Princeston Street Big storm drain, Princeston Street Round storm drain, Cove Road West storm drain, and Union Street storm drain, enterococci levels were only sampled once in which levels were ~426 CFU per 100 mL, ~1267 CFU per 100 mL, ~551 CFU per 100 mL, and ~722 CFU per 100 mL, respectively (Fig. 23A). Average enterococci levels at the Amherst Road storm drain, Princeston Street North storm drain, Cove Road storm drain, Windmill Beach outfall pipe, Cormaria outfall pipe, Haven's Beach Sump Pipe and Azurest Beach storm drain during the summer were ~293 CFU per 100 mL, ~3398 CFU per 100 mL, ~2072 CFU per 100 mL, ~1257 CFU per 100 mL, ~1716 CFU per 100 mL, ~1204 CFU per 100 mL, and ~2184 CFU per 100 mL, respectively (Fig. 23B).

3.3.2. Total nitrogen levels

Total nitrogen levels at the Amherst Road storm drain, Princeston Street North storm drain, Princeston Street Big storm drain, Princeston Street Road storm drain, Cove Road storm drain, Windmill Beach outfall pipe, Cormaria outfall pipe, and Haven's Beach Sump Pipe ranged ~0.17-1.41 mg N/L, ~1.99-2.31 mg N/L, ~0.79-0.89 mg N/L, ~0.53-2.91 mg N/L, ~1.02-2.39 mg N/L, ~1.69-3.15 mg N/L, ~0.57-2.35 mg N/L, and ~0.93-1.62 mg N/L, respectively (Fig. 24A). Total nitrogen levels at the Cove Road West storm drain were found on only one date (31-May-2024) in which the level was 1.19 mg N/L (Fig. 24A). Average total nitrogen levels at the Amherst Road storm drain, Princeston Street North storm drain, Princeston Street Big storm drain, Princeston Street Road storm drain, Cove Road storm drain, Windmill Beach outfall pipe, Cormaria outfall pipe, and Haven's Beach Sump Pipe during summer 2024 were ~0.91 mg N/L, ~2.15 mg N/L, ~1.13 mg N/L, ~1.66 mg N/L, ~1.68 mg N/L, ~2.51 mg N/L, ~1.34 mg N/L, and ~1.37 mg N/L (Fig. 24B). Total nitrogen levels was not sampled from the Union Street storm drain nor Azurest Beach storm drain during summer 2024.

4. MANAGEMENT OPTIONS

Management of pathogens in surface waters of Sag Harbor Village is warranted. Fecal coliform bacteria levels exceeded the NYSDEC standard for shellfishing (14 CFU per 100 mL) at all Haven's Beach sites on multiple occasions in 2024 (~40% of samples). Similarly, Enterococcus levels exceeded the NYSDOH swimming standard (104 CFU per 100 mL) in ~41% of samples in summer 2024 at Haven's Beach. Yet, Haven's Beach remains open to shellfishing and is a bathing beach locale. At the Sag Harbor marine sites, fecal coliform levels were above the NYSDEC shellfishing standard for ~48% of the samples, while Enterococcus levels exceeded the NYSDOH swimming standard in ~45% of samples. Furthermore, across storm drains, fecal coliform levels surpassed the NYSDEC standard for shellfishing in ~95% of samples and Enterococcus levels exceeded the NYSDOH swimming standard in ~92% of samples.

During 2019-2023, microbial source tracking revealed that the sources of fecal bacteria differed by time and location and primarily included dogs and small mammals, humans, and birds, which is consistent with the findings in 2024. In 2024, dogs and small mammals had the strongest signal in a majority of the Sag Harbor marine sites and Haven's Beach sites. Only at Notre Dame were birds the strongest source of fecal bacteria. Humans and ruminants made up less than 13% of fecal bacteria at any marine or Haven's Beach site.

Studies by the Gobler Lab a decade ago identified high levels of fecal bacteria in the Haven's Beach region, which have persisted into the current decade. Given the location of the sump adjacent to these waters, the creation of an expanded buffer system to intercept and divert run-off from these sites into surface water would reduce the delivery of pathogens. Still, fecal contamination within the inner harbor presents another situation. The sewage treatment plant is likely a minor source of bacteria for this region, in addition to boats and street run-off. Given the findings at Windmill Beach, it may be prudent to close this site to swimming or perform enhanced monitoring.

During 2024, at marine locations within Sag Harbor, water quality was consistent with 2023 findings and was improved in some respects from studies prior to 2021. At most locations for most dates, dissolved oxygen levels were above the NYSDEC dissolved oxygen minimum (4.8 mg L⁻¹), while average chlorophyll *a* concentration at each site were mostly below the USEPA chlorophyll *a* maximum for marine systems (20 µg L⁻¹). As in 2023, neither *Dinophysis* nor *Cochlodinium* exceeded bloom thresholds, and *Alexandrium* was not found at any point during the sampling season at a majority of sampled sites. However, in 2024, *Dinophysis* and *Cochlodinium* were present at Sag Harbor Cove, Amherst Road, Cove Road, and Windmill Beach with more *Dinophysis* presence and less *Cochlodinium* presence, compared to 2023. Additionally, *Alexandrium* was present at Sag Harbor Cove and exceeded its respective bloom threshold on two dates in 2024 at the site. While *Cochlodinium* concentrations were low due to the sampling season beginning in late August 2024, *Cochlodinium* was prevalent at a majority of marine sites in Sag Harbor during 2022, and exceeded its bloom threshold several times throughout 2022, in which it is considered harmful to marine life. This shows that nitrogen (N) impairment is a continued issue for Sag Harbor. The presence of *Cochlodinium*, *Alexandrium*, and *Dinophysis* have been shown to be promoted by excessive N loading (Gobler et al., 2012).

Given the ability of N to increase phytoplankton biomass, the exceedance of guidance values for total N, algae, and water clarity, and the occurrences of harmful rust tides that are promoted by excessive N, reductions in N loading across the region are warranted. Total nitrogen levels were higher at all the Sag Harbor storm drain sites than at the Haven's Beach and marine sites, in 2024. Given that the overwhelming majority of N entering this region emanates from onsite septic systems, upgrading these systems and/or connecting homes to the sewage treatment plant would be the most effective approaches. While a more fine-scale study of pathogenic bacteria may be needed to optimize remedial approaches, minimizing or rerouting surface discharge of water from the Haven's Beach sump or Otter Pond may be effective management approaches.

In 2016, Suffolk County adopted Article 19 of the sanitary code which permitted the use of innovative and alternative septic systems. Such systems must reduce total nitrogen levels in septic effluent to less than 19 mg L⁻¹ and, to date, five such commercially available systems have been approved for use. Additional systems are in the piloting stage of approval, making the array of choices even larger in the future. For example, the NYS Center for Clean Water Technology at Stony Brook University is piloting Nitrogen Removing Biofilters as onsite septic systems which have been achieving septic effluent of < 10 mg L⁻¹ as well as >90% removal of drugs, pharmaceuticals, personal care products, and other organic contaminants. Presently, Suffolk County, the Town of East Hampton Town and the Town of Southampton all have grants available to homeowners to install any of the Article 19-approved low nitrogen septic systems. The cost of a 'simple' installation of the low nitrogen systems is presently ~\$25,000, but much more for a complex site. The sum of grants available is often more than the cost of the full installation of the systems, meaning that, in many cases, they can be installed for free. In some cases, however, installation can become more expensive if, for example, major infrastructure or landscaping must be moved or replaced during the installation process.

Beyond the upgrading of septic systems, there are likely opportunities to connect parts of Sag Harbor Village to the existing sewage treatment plant. The plant is currently discharging very low levels of N to surface waters, on average $< 5 \text{ mg L}^{-1}$, which is better than any approved onsite septic system. For regions near the sewage treatment plant, it may be cost effective to hook up homes and facilities to the existing plant. This must be fully investigated, however, as for some parts of Long Island such costs can exceed \$50,000 per home and the installation of sewage lines can be disruptive to neighborhoods. Still, once connected, the installation would create a maintenance-free solution for homeowners although the connection to the sewage treatment plant will represent an additional utility fee. For onsite systems, Suffolk County requires homeowners to purchase operation and maintenance contracts with certified companies who will inspect systems one-to-two times per year to assure systems are functioning properly.

In 2021, Suffolk County completed its Subwatersheds study and declared that Sag Harbor Cove should strive for a 62% to 81% N reduction to achieve water quality improvements, levels that could be achieved by upgrading septic systems. In contrast, the same study declared Sag Harbor was not a high priority for water quality improvement due to an absence of HABs and hypoxia during Suffolk County monitoring during the past decade. These findings are generally consistent with those of this study which also found water quality impairment was more significant in Sag Harbor Cove compared to Sag Harbor Bay. Our utilization of more high frequency monitoring compared to Suffolk County allowed for the detection of transient harmful algal blooms and hypoxia in Sag Harbor. Collectively, both studies prioritize N reductions in Sag Harbor Cove over Sag Harbor Bay.

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6. FIGURES AND TABLES

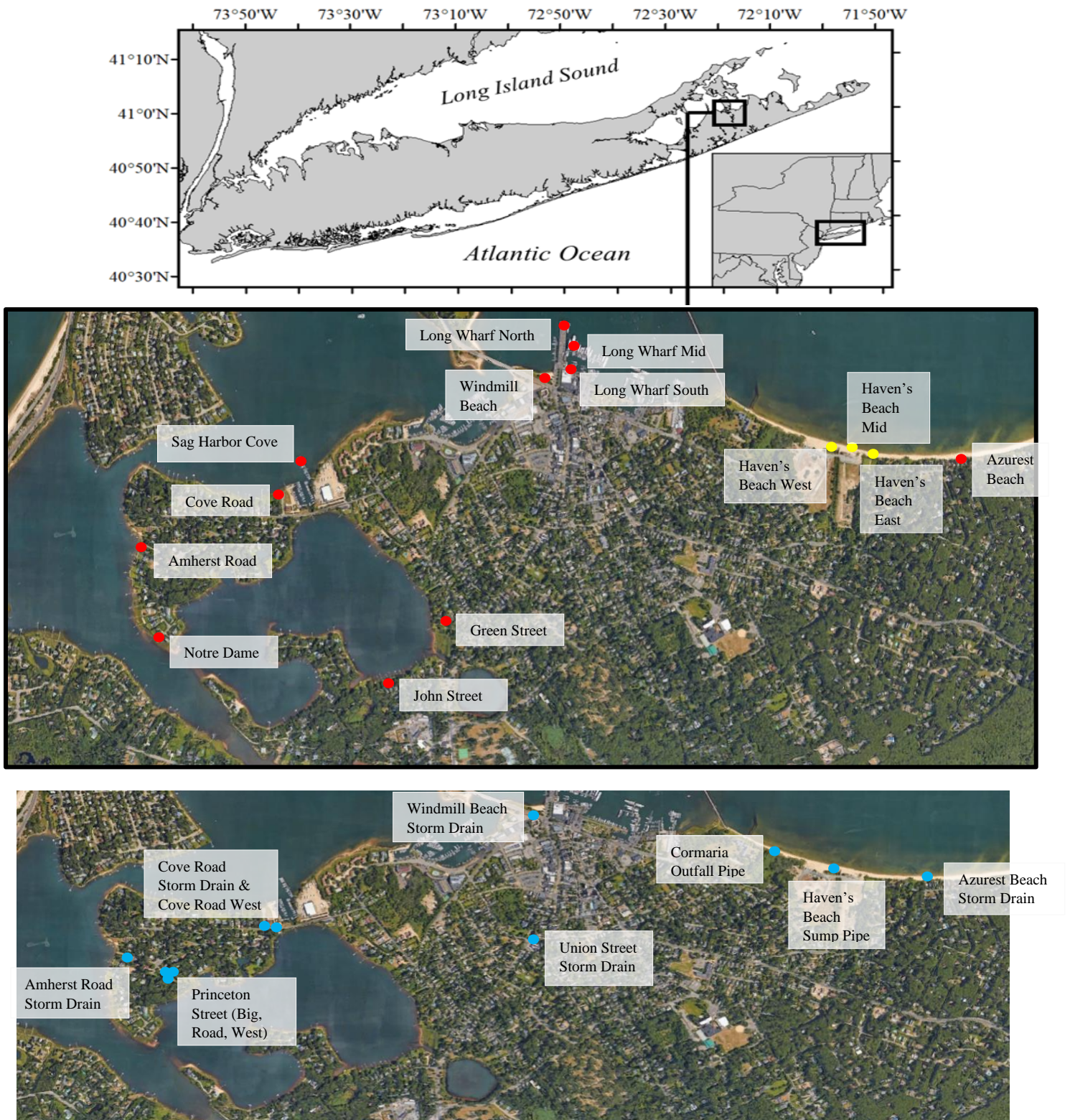


Figure 1. Map of Sag Harbor sample sites during 2024. Marine sampling sites are red, Haven's Beach sampling sites are yellow, and storm drain sampling sites are blue.

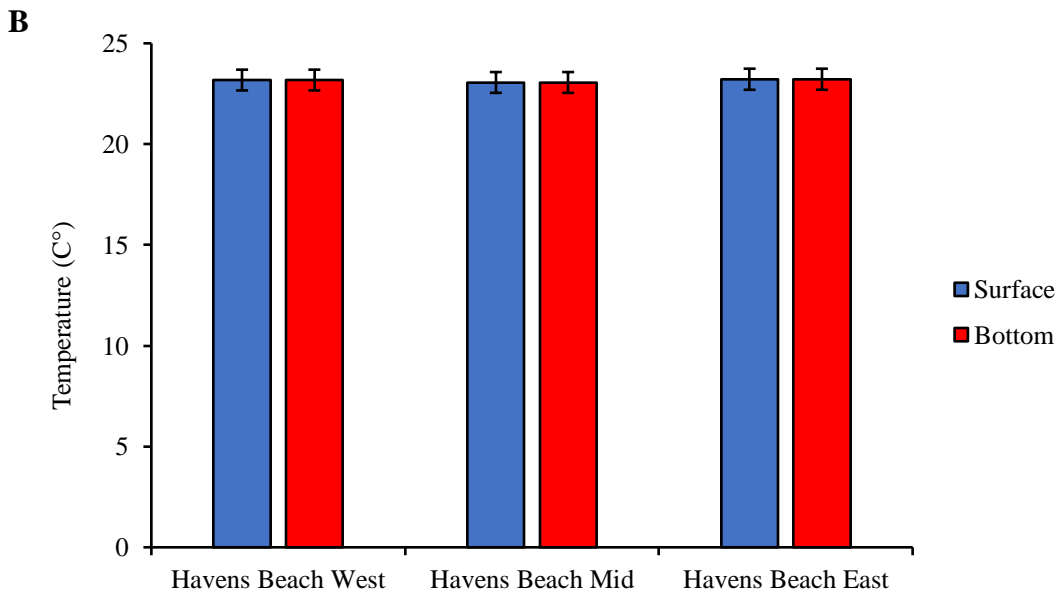
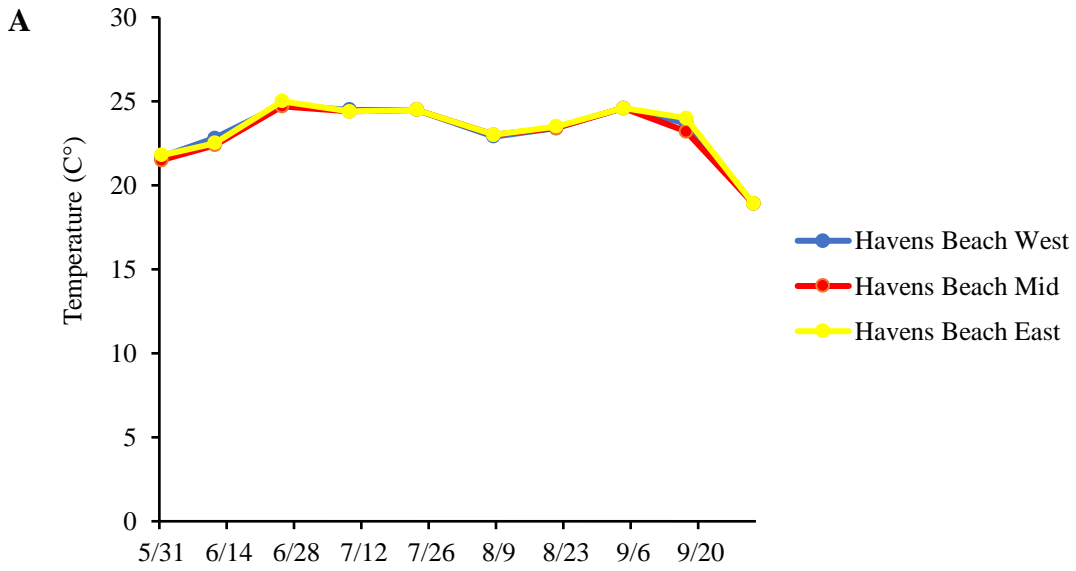


Figure 2. A.) Time-series, and B.) Average surface and bottom water temperatures (°C) across Haven’s Beach in Sag Harbor during 2024. Columns represent means \pm standard error.

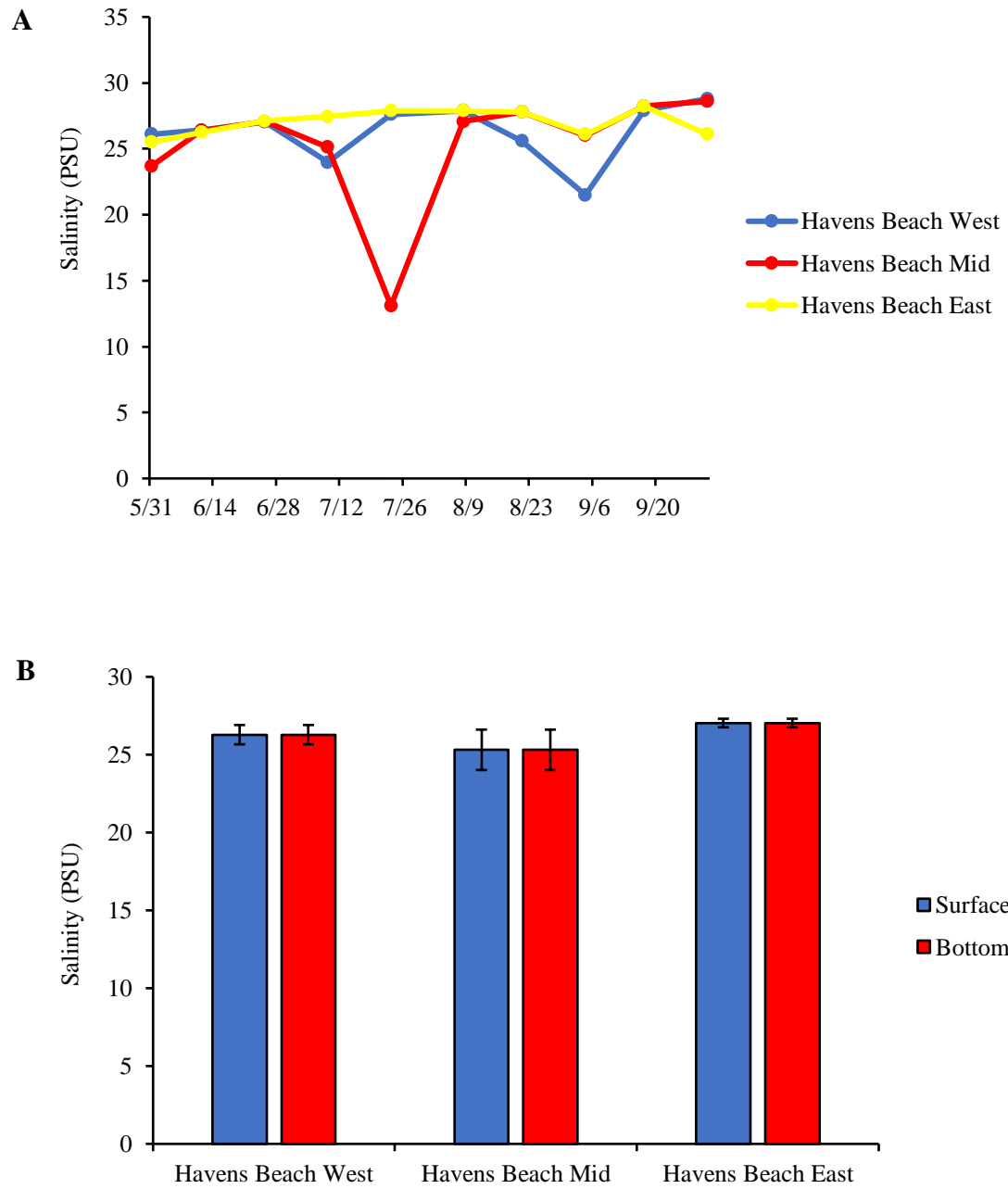


Figure 3. A.) Time-series, and B.) Average surface and bottom water salinities (PSU) across Haven’s Beach in Sag Harbor during 2024. Columns represent means \pm standard error.

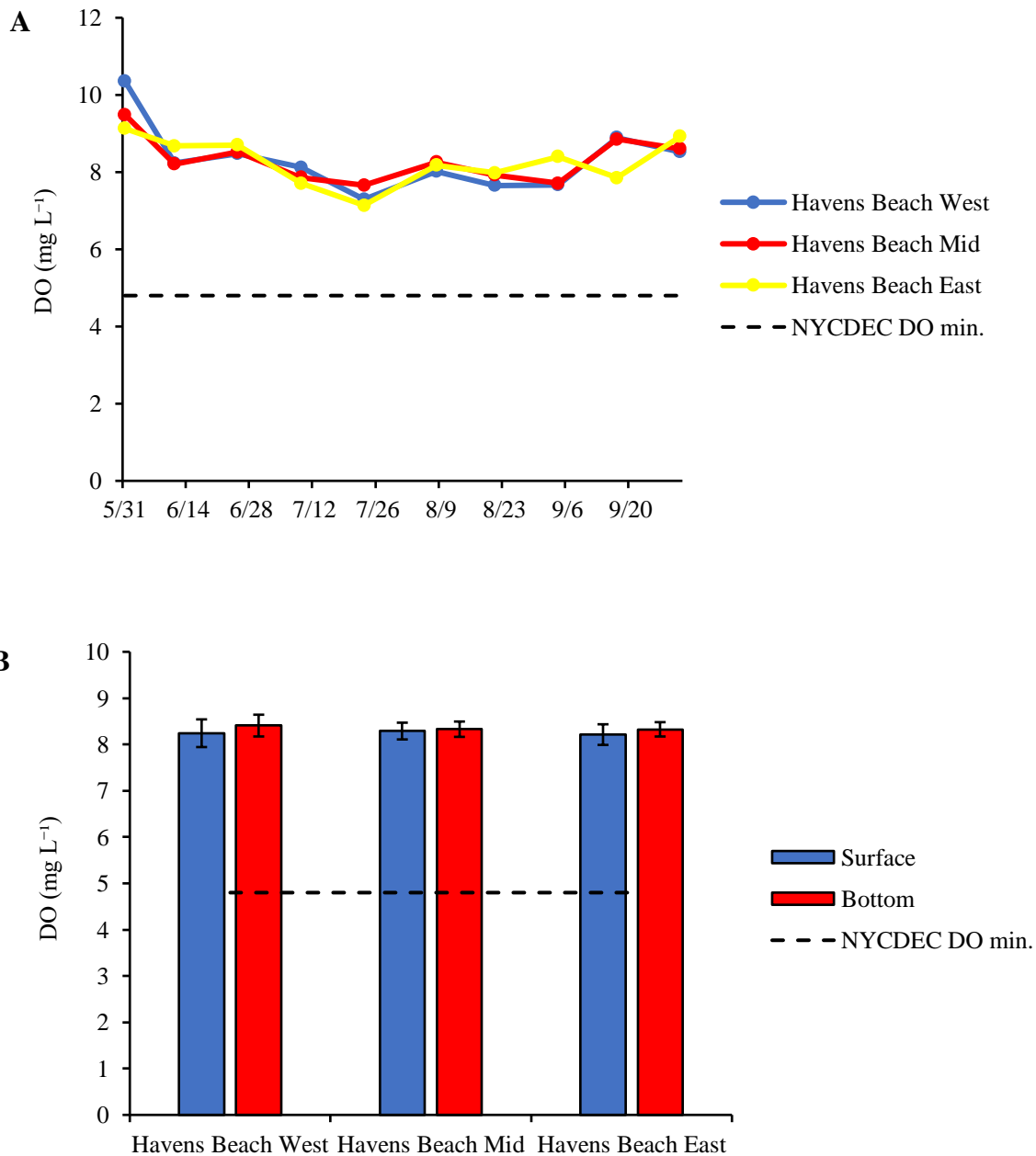


Figure 4. A.) Time-series, and B.) Average surface and bottom dissolved oxygen concentrations (mg L^{-1}) across Haven’s Beach in Sag Harbor during 2023. Columns represent means \pm standard error.

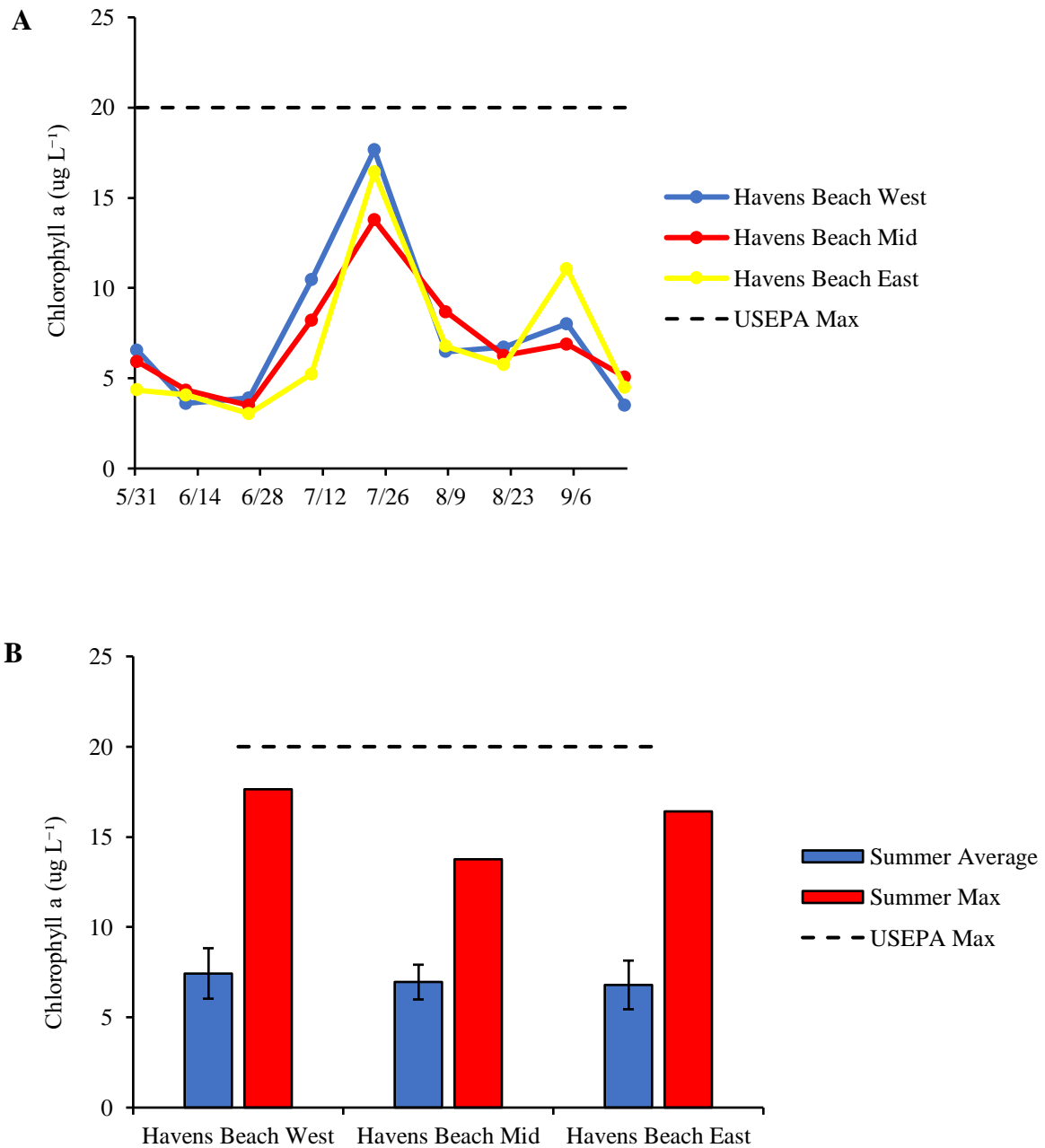


Figure 5. A.) Time-series, and B.) Summer average and maximum chlorophyll *a* concentration ($\mu\text{g L}^{-1}$) across Haven’s Beach in Sag Harbor during 2023. Columns represent means \pm standard error.

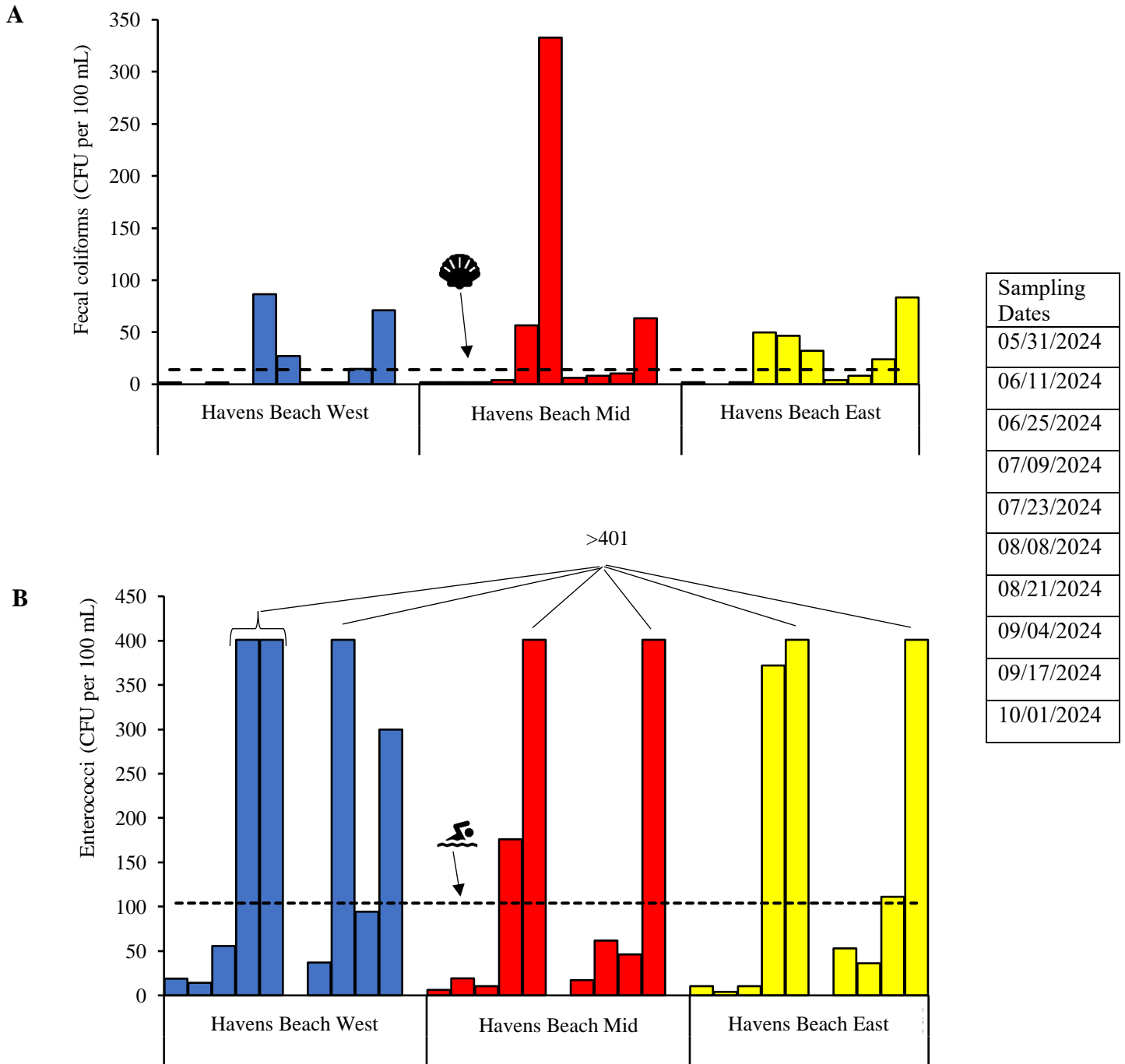


Figure 6. Time-series of A.) Fecal coliform and B.) Enterococci concentrations (CFU per 100 mL) across Haven's Beach in Sag Harbor during 2024.

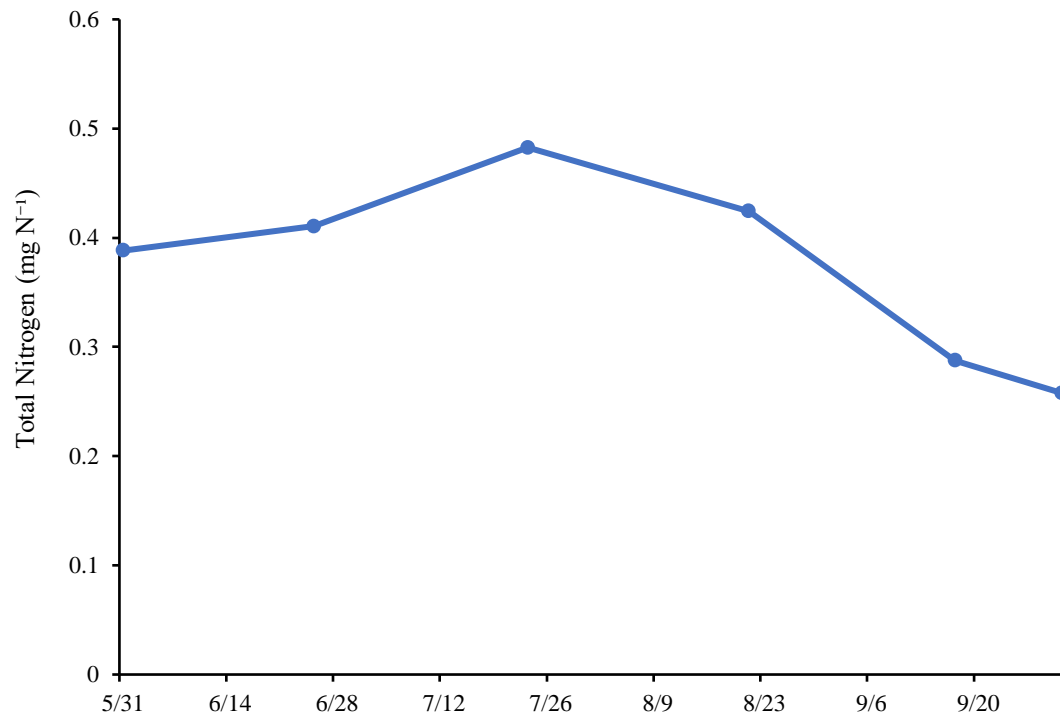


Figure 7. Time-series of total nitrogen levels (mg N/L) at Haven’s Beach Mid in Sag Harbor during 2024.

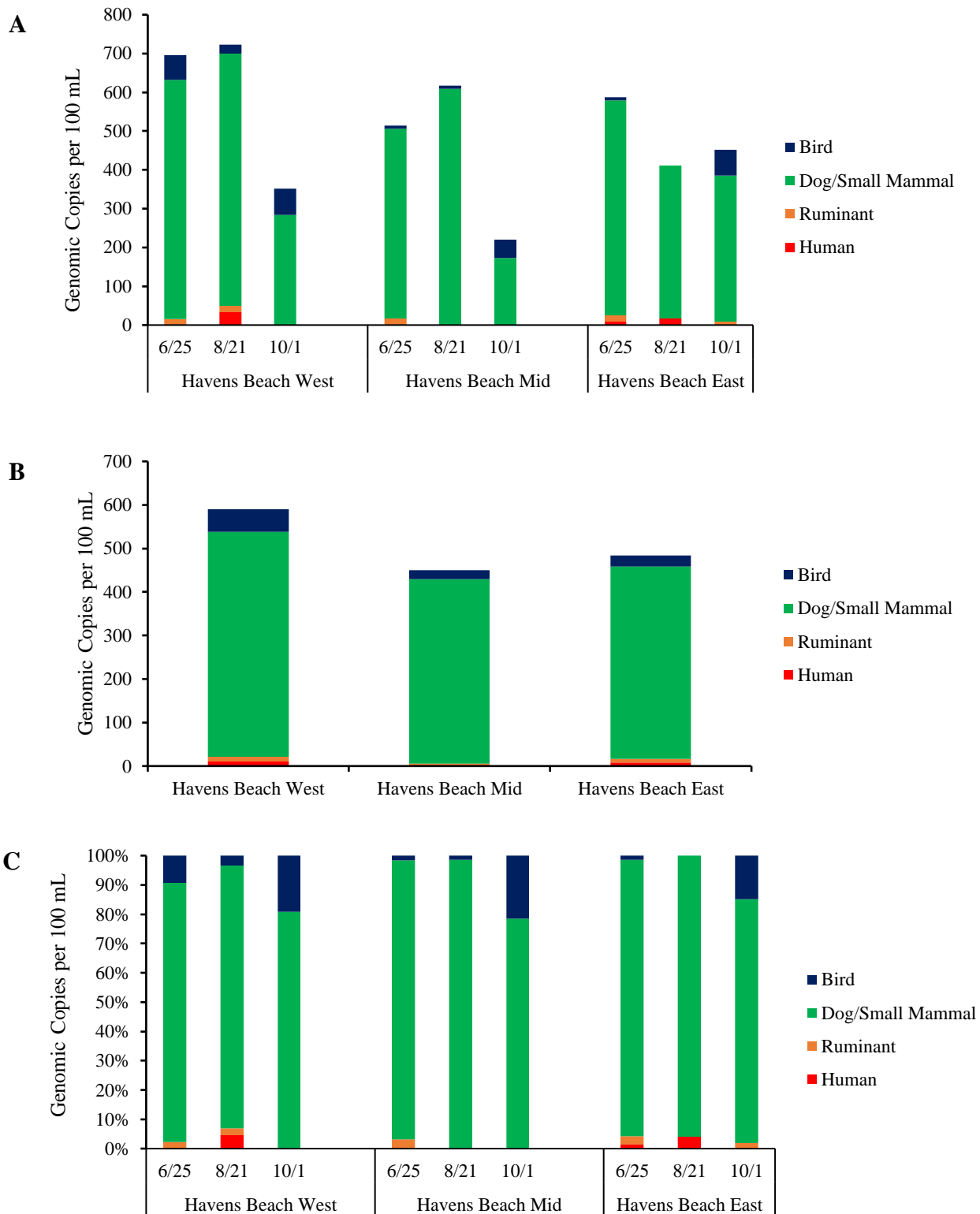


Figure 8. A.) Time-series, B.) Summer averages, and C.) Average relative abundances of fecal bacteria (split into human, ruminant, dog/small mammal, and bird) (genomic copies per 100ml) across Haven’s Beach in Sag Harbor during 2024.

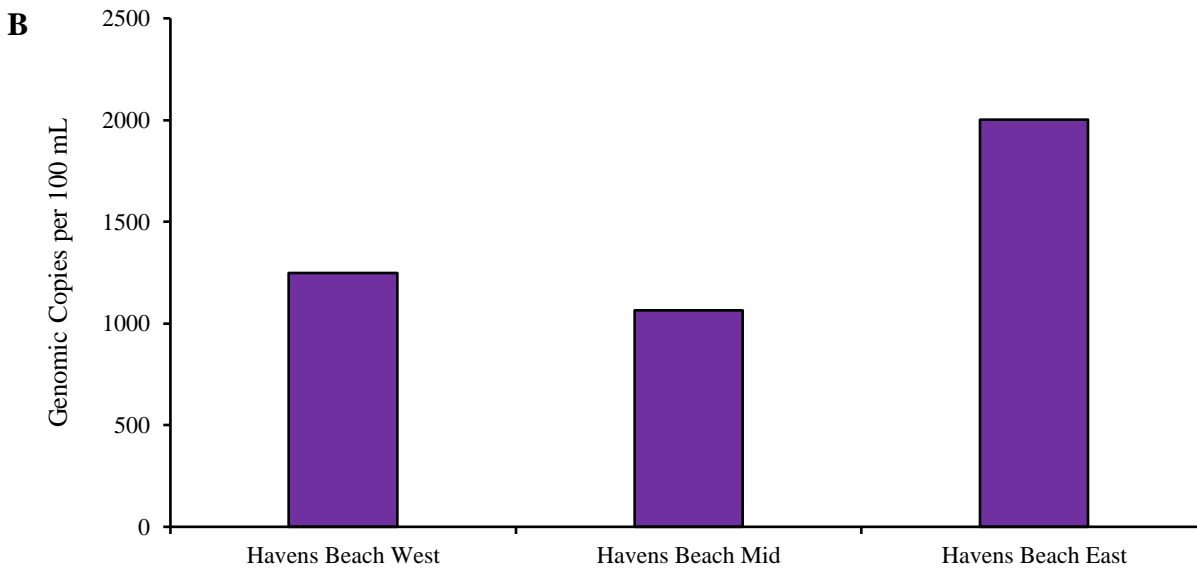
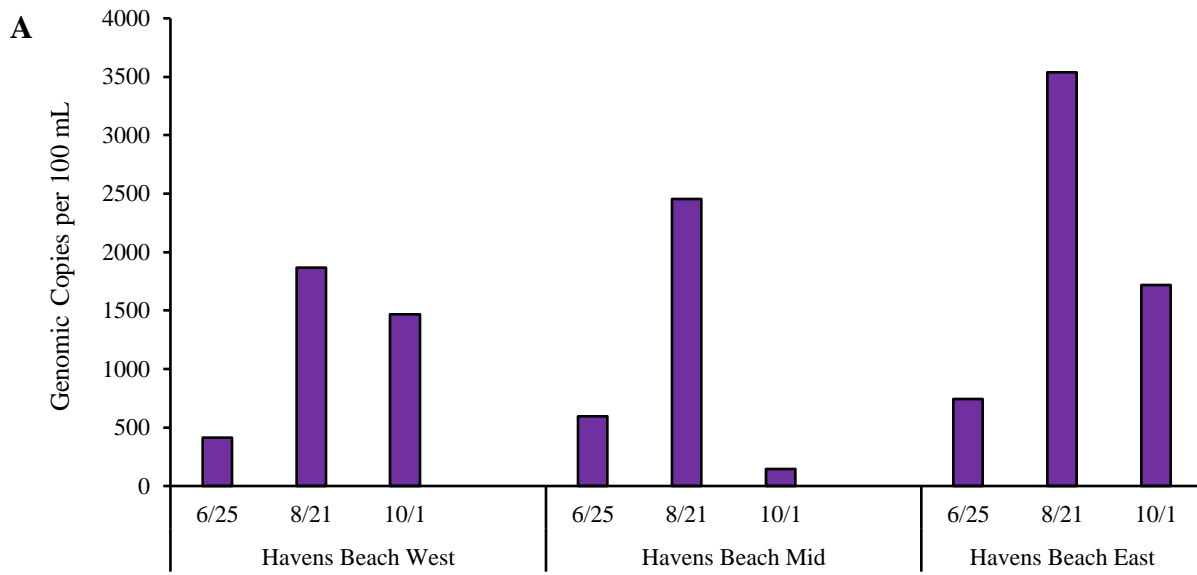


Figure 9. A.) Time-series, and B.) Summer averages of enterococcus concentrations (genomic copies per 100ml) across Haven’s Beach in Sag Harbor during 2024.

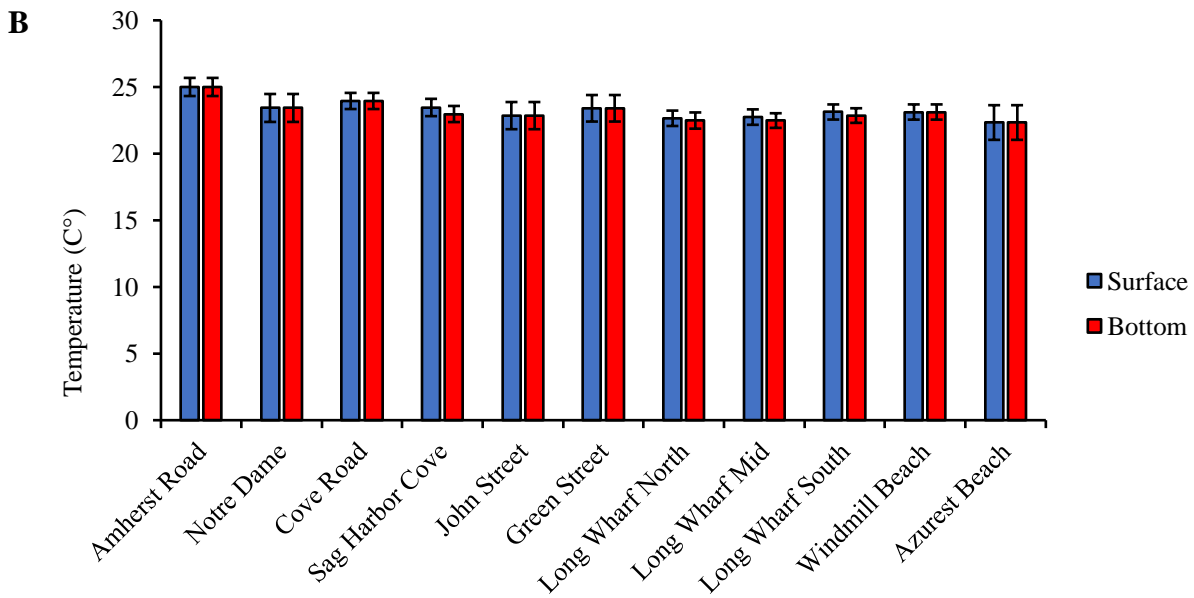
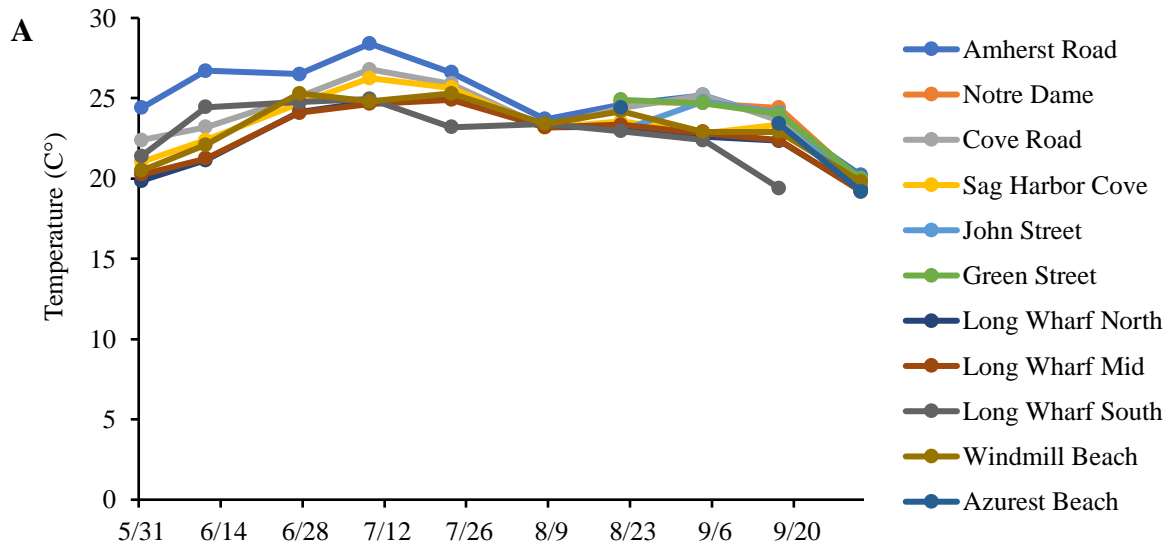


Figure 10. A.) Time-series, and B.) Average surface and bottom water temperatures (°C) across marine sites in Sag Harbor during 2024. Columns represent means \pm standard error.

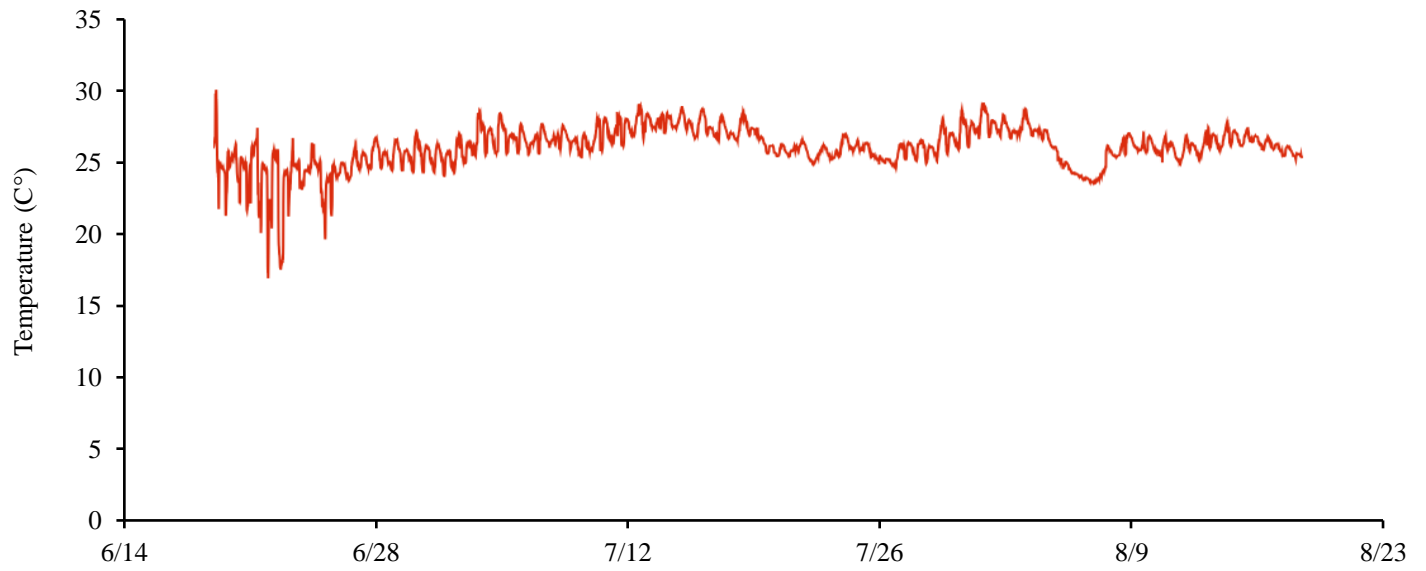


Figure 11. Continuous measurements of temperature (°C) taken from a HOBO temperature/dissolved oxygen logger deployed at the Sag Harbor Cove site during summer 2024.

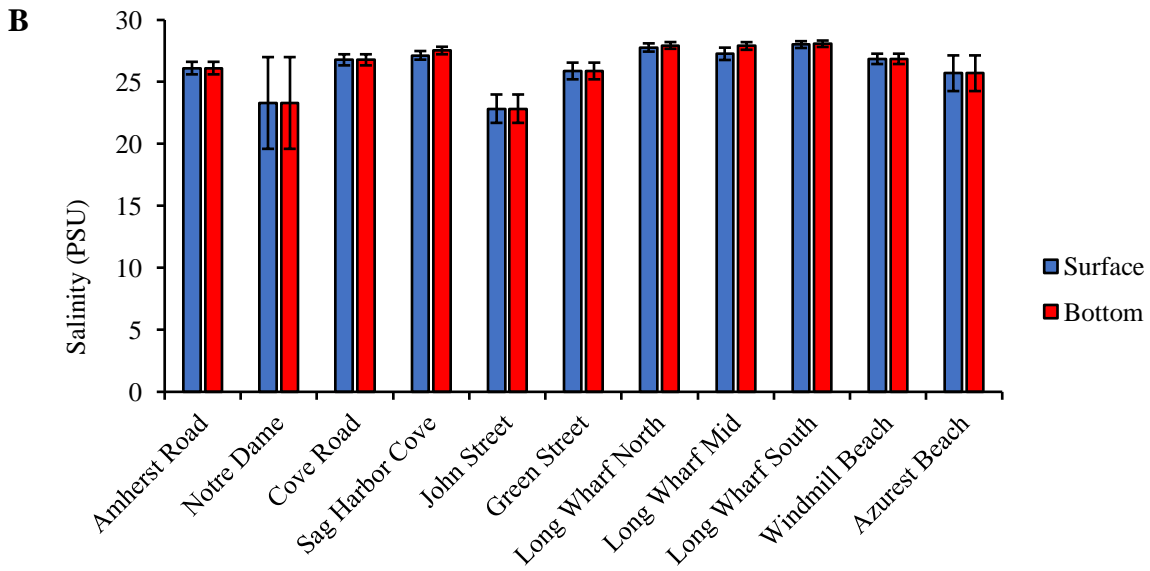
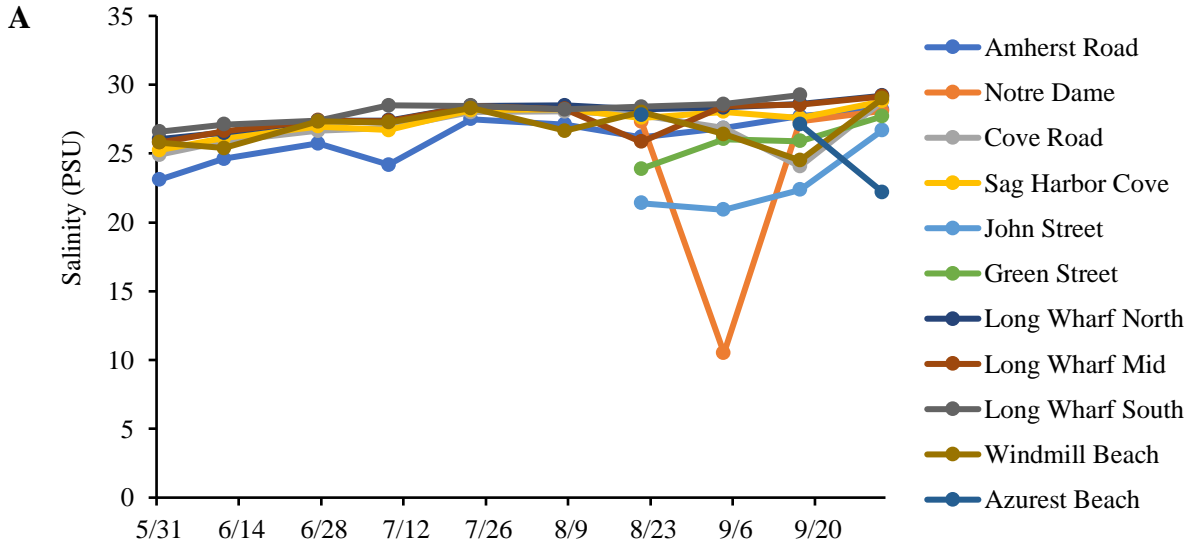


Figure 12. A.) Time-series, and B.) Average surface and bottom water salinities (PSU) across marine sites in Sag Harbor during 2024. Columns represent means \pm standard error.

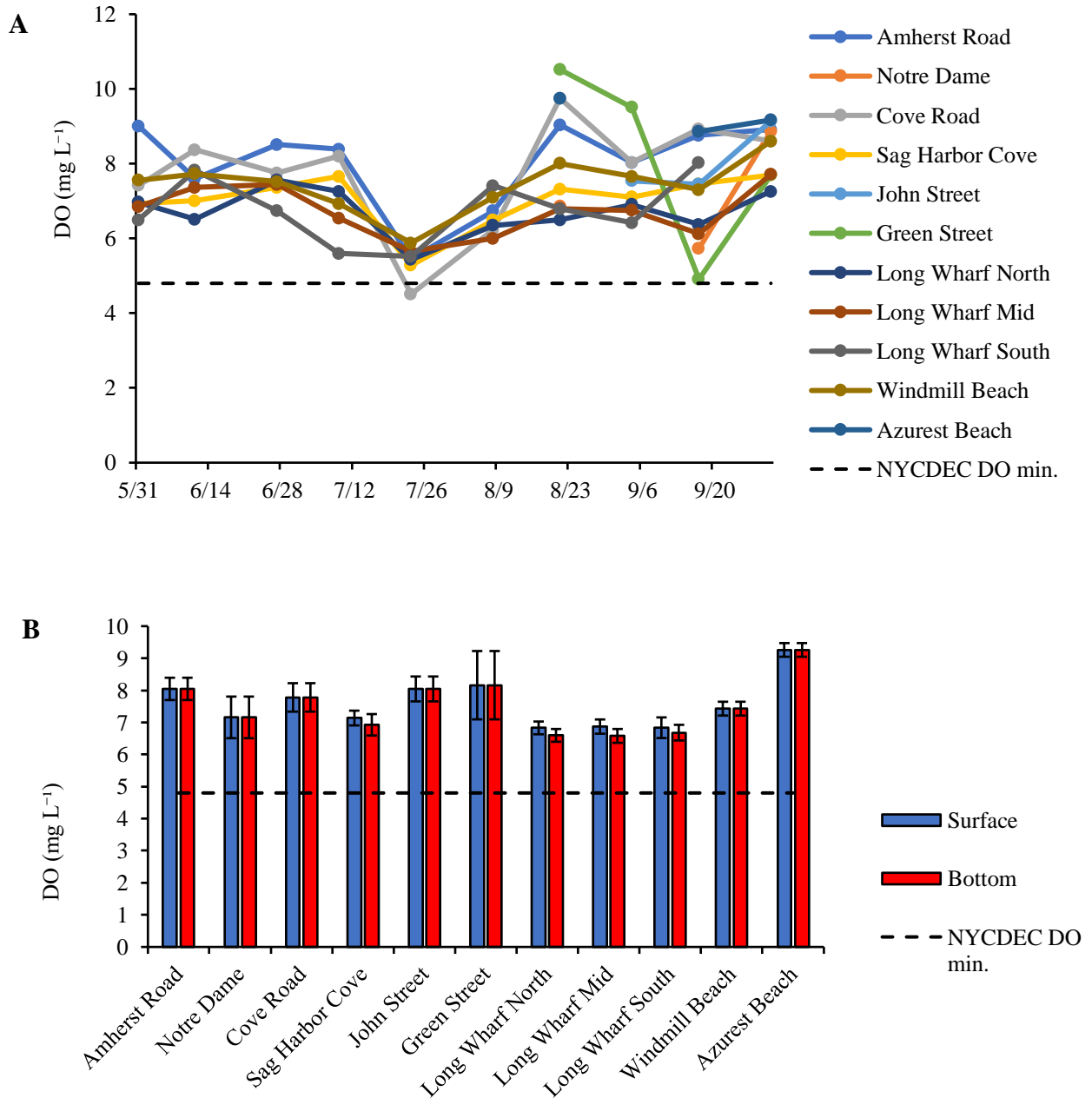


Figure 13. A.) Time-series, and B.) Average surface and bottom dissolved oxygen concentrations (mg L⁻¹) across marine sites in Sag Harbor during 2023. Columns represent means \pm standard error.

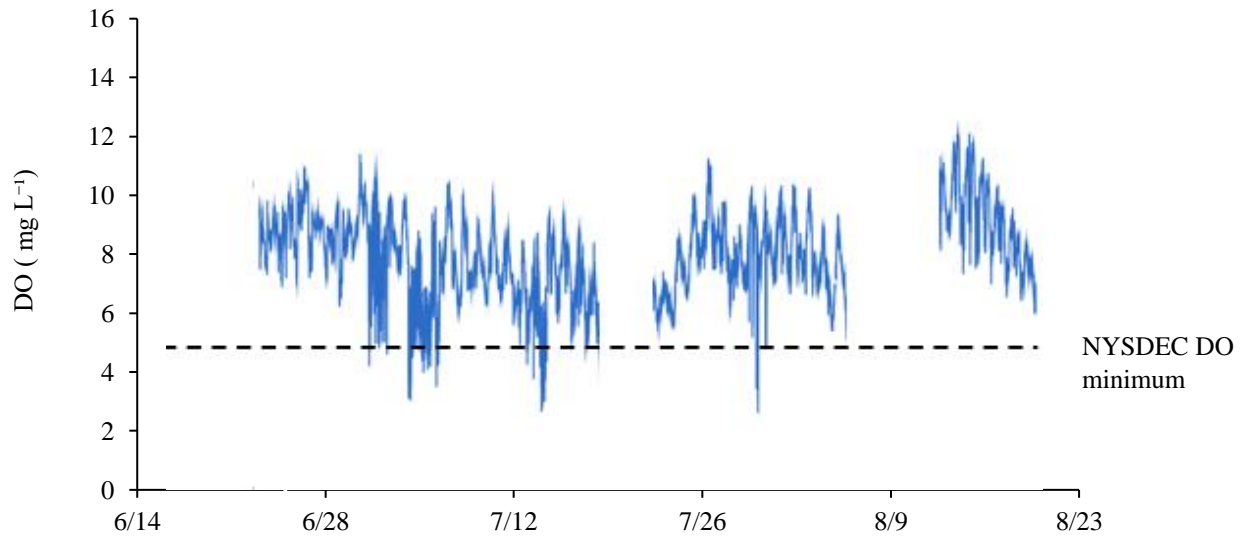


Figure 14. Continuous measurements of dissolved oxygen (mg L^{-1}) taken from a HOBO temperature/dissolved oxygen logger deployed at the Sag Harbor Upper Cove during summer 2024.

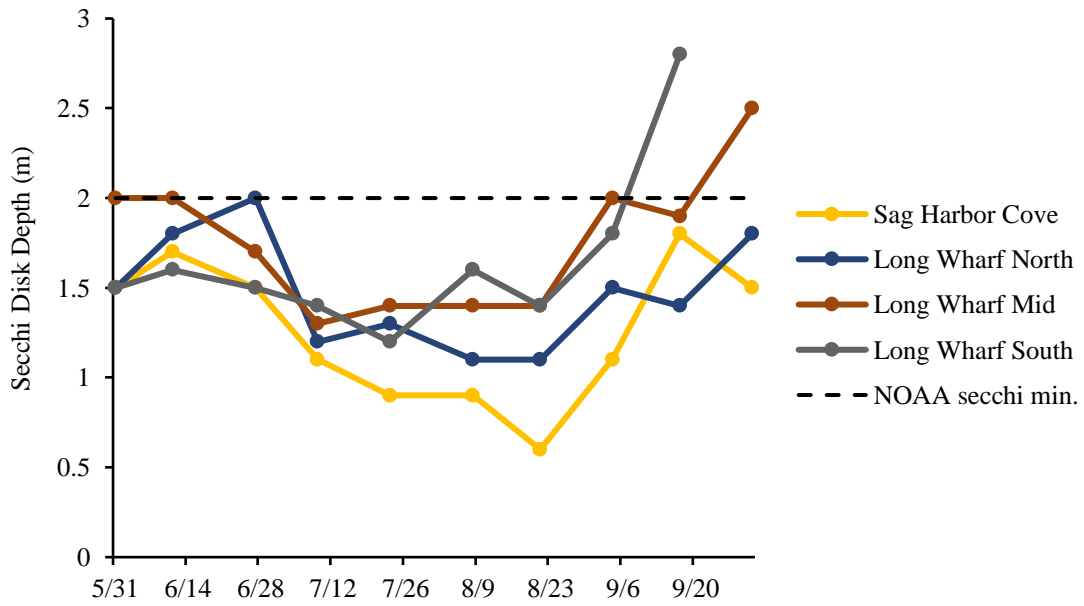


Figure 15. Secchi disk depths (m) across marine sites in Sag Harbor during 2024.

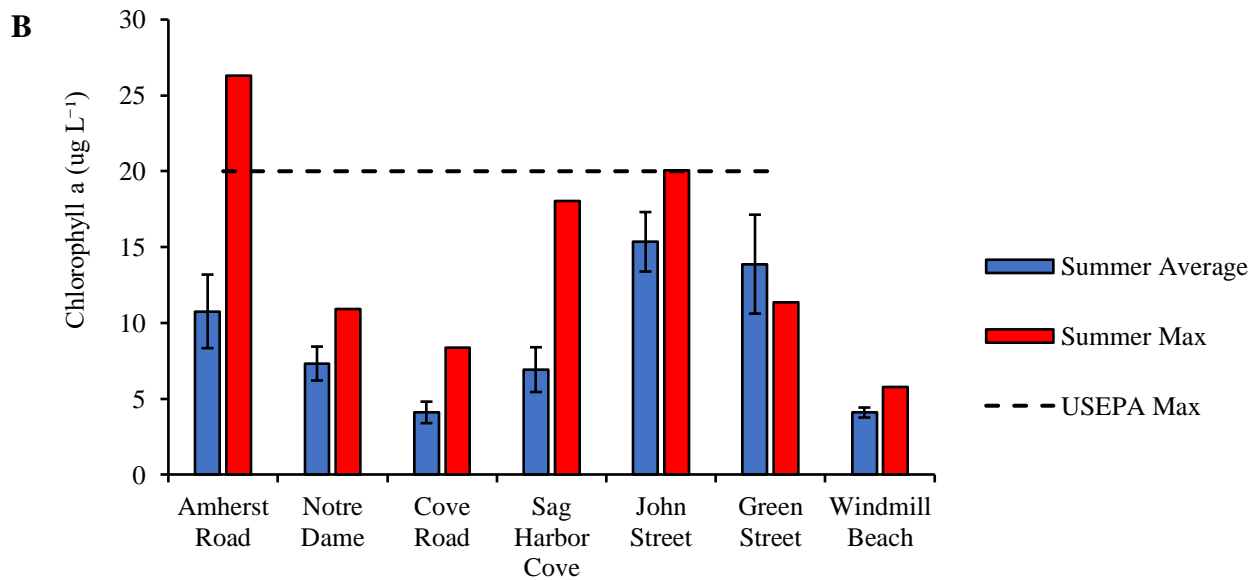
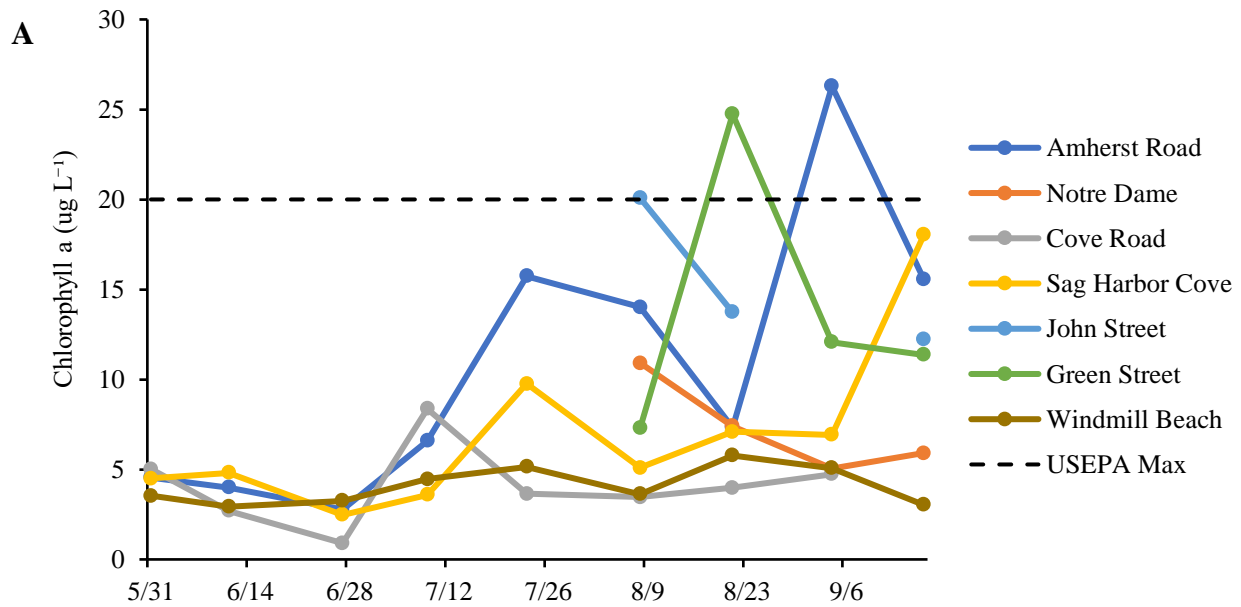


Figure 16. A.) Time-series, and B.) Summer average and maximum chlorophyll *a* concentration ($\mu\text{g L}^{-1}$) across marine sites in Sag Harbor during 2024. Columns represent means \pm standard error.

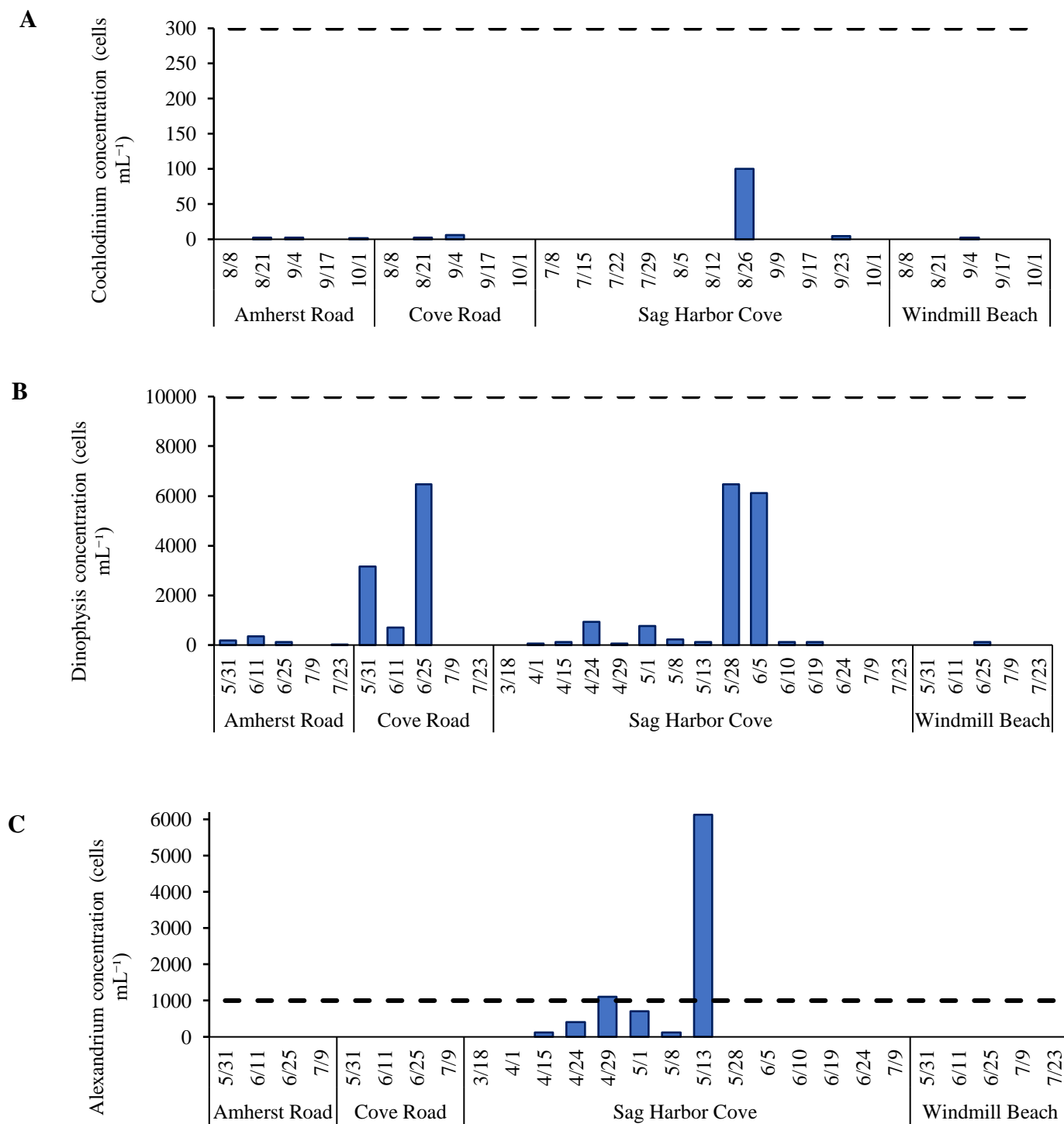
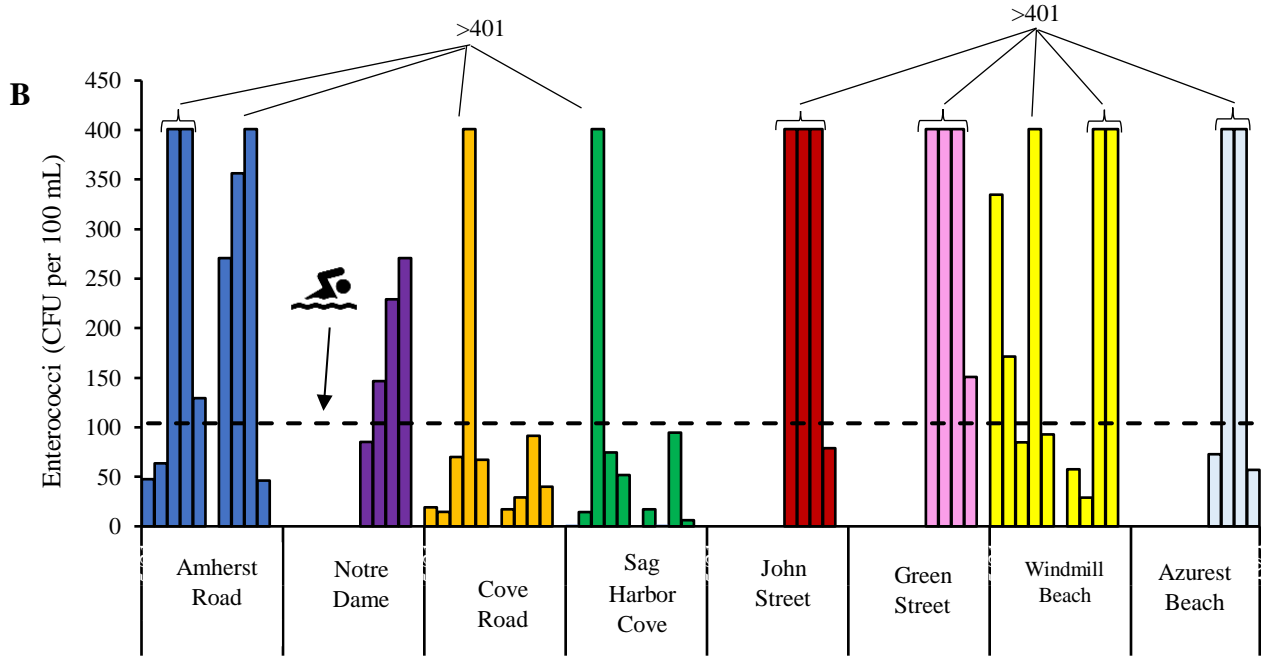
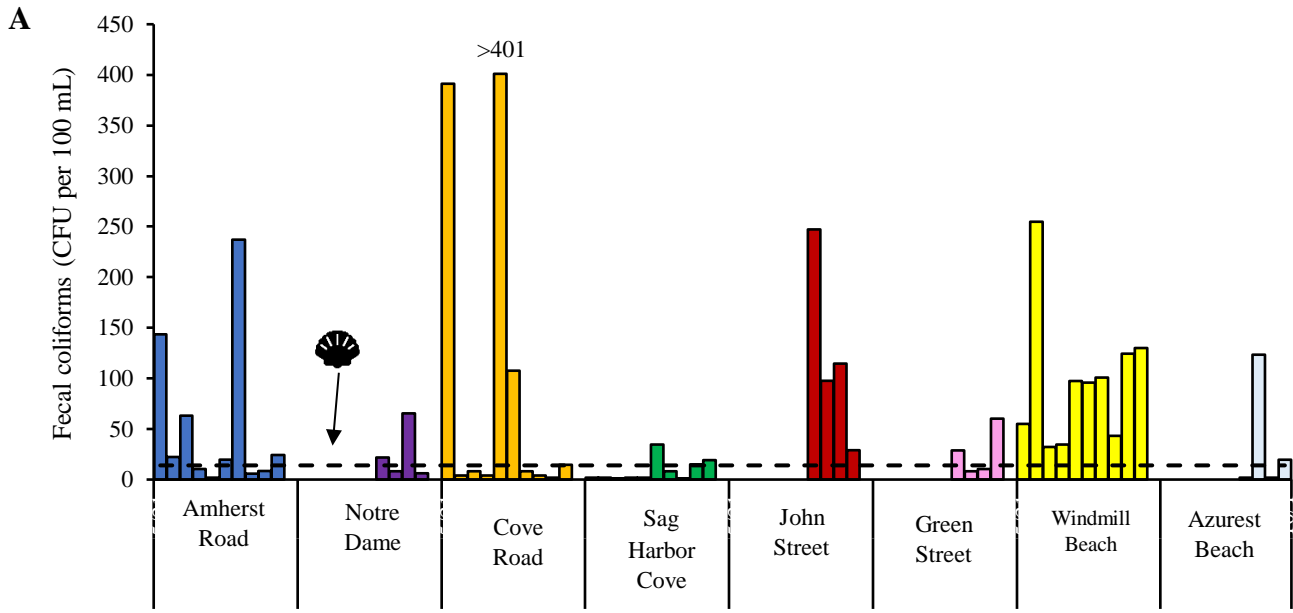


Figure 17. Concentrations of A.) *Cochlodinium*, B.) *Dinophysis*, and C.) *Alexandrium* (cells mL⁻¹) across marine sites in Sag Harbor during 2024. The dashed lines represent respective bloom thresholds. *Dinophysis* threshold is 10,000 cells per mL, and *Cochlodinium* threshold is 300 cells per mL.



Sampling Dates
05/31/2024
06/11/2024
06/25/2024
07/09/2024
07/23/2024
08/08/2024
08/21/2024
09/04/2024
09/17/2024
10/01/2024

Figure 18. Time-series of A.) Fecal coliform and B.) Enterococci concentrations (CFU per 100 mL) across marine sites in Sag Harbor during 2024.

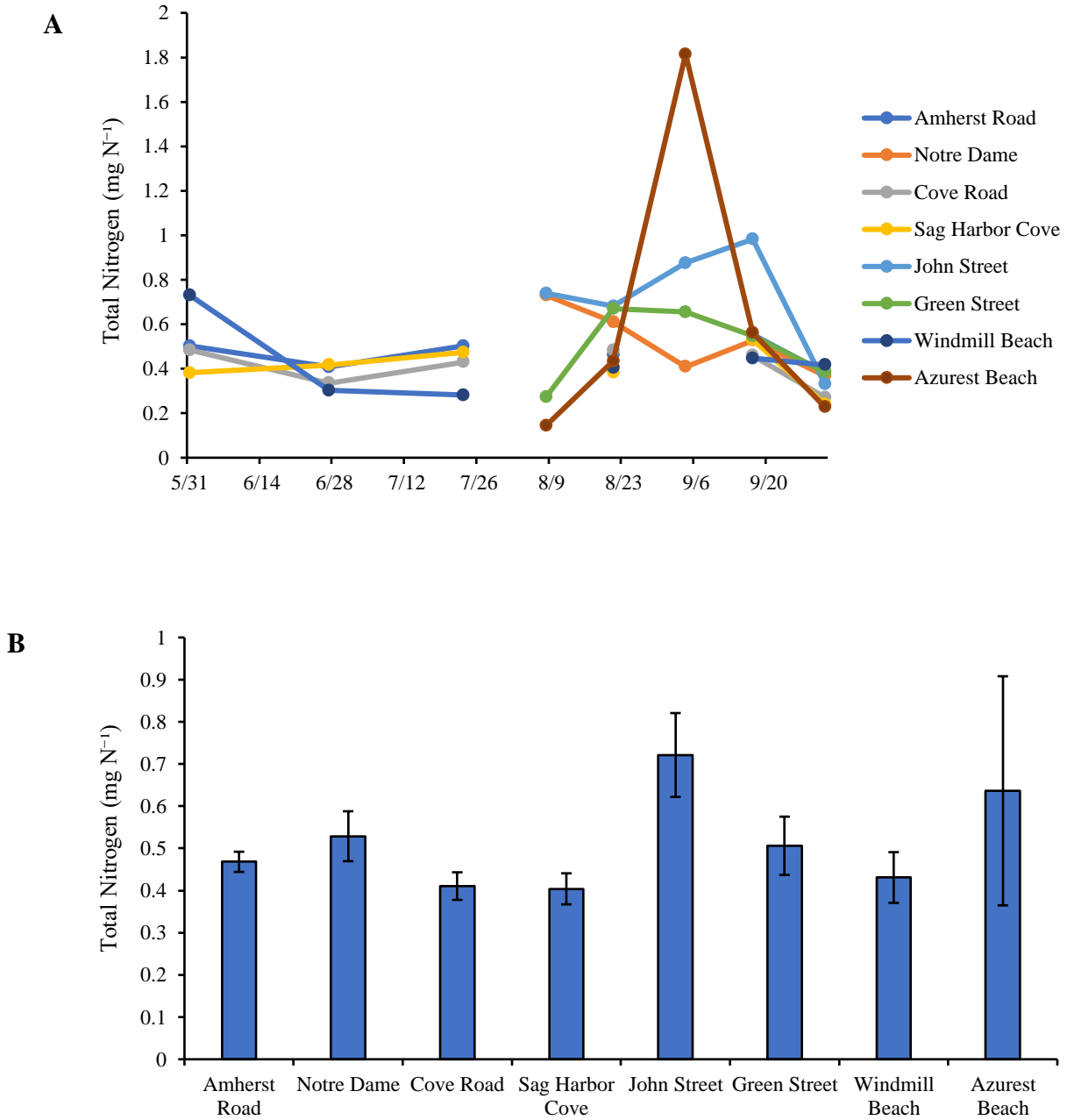


Figure 19. A.) Time-series, and B.) Summer average of total nitrogen levels (mg N/L) at Sag Harbor marine sites during 2024. Columns represent means \pm standard error.

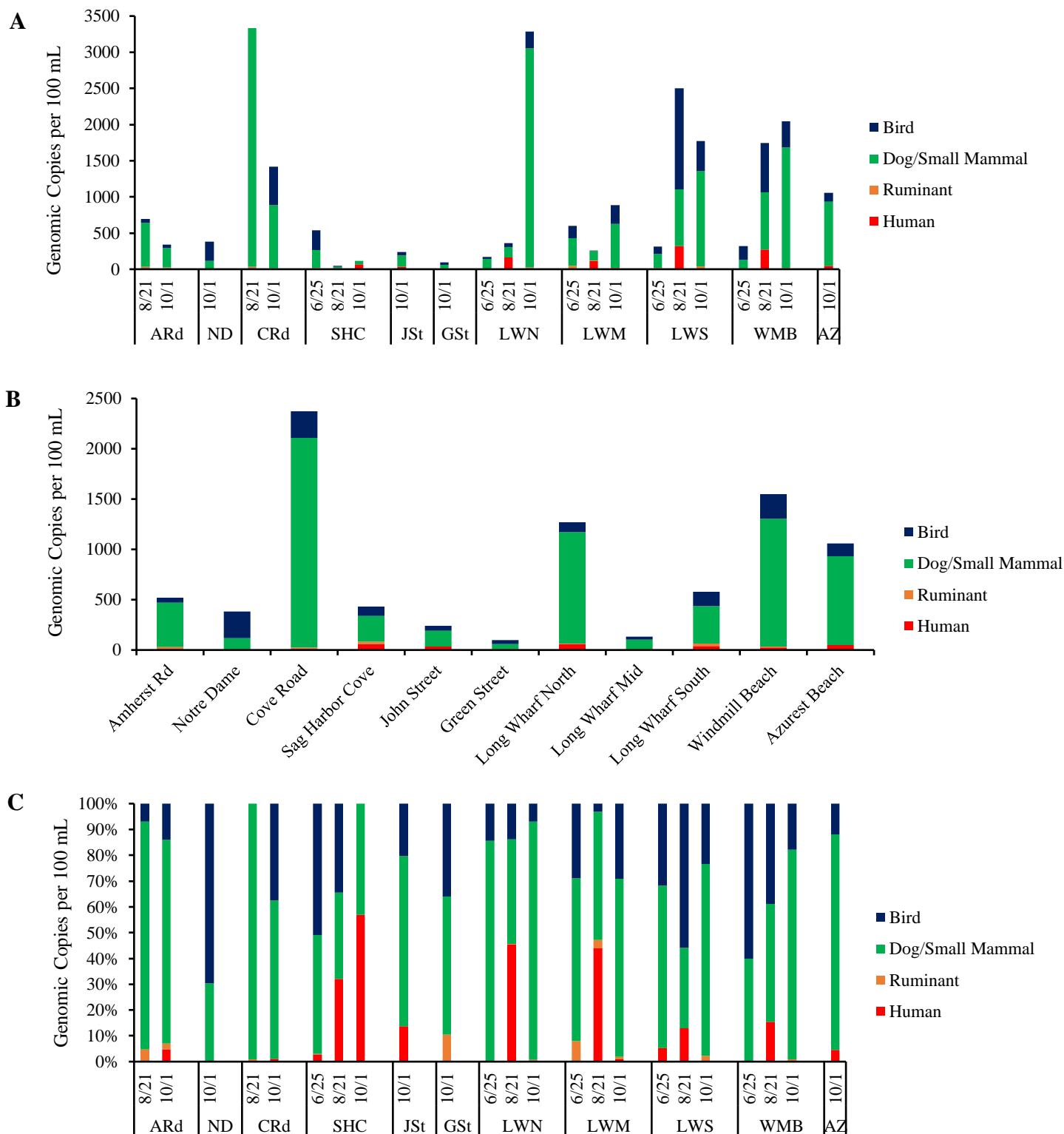


Figure 20. A.) Time-series, B.) Summer averages, and C.) Average relative abundances of fecal bacteria (split into human, ruminant, dog/small mammal, and bird) (genomic copies per 100ml) across marine sites in Sag Harbor during 2024.

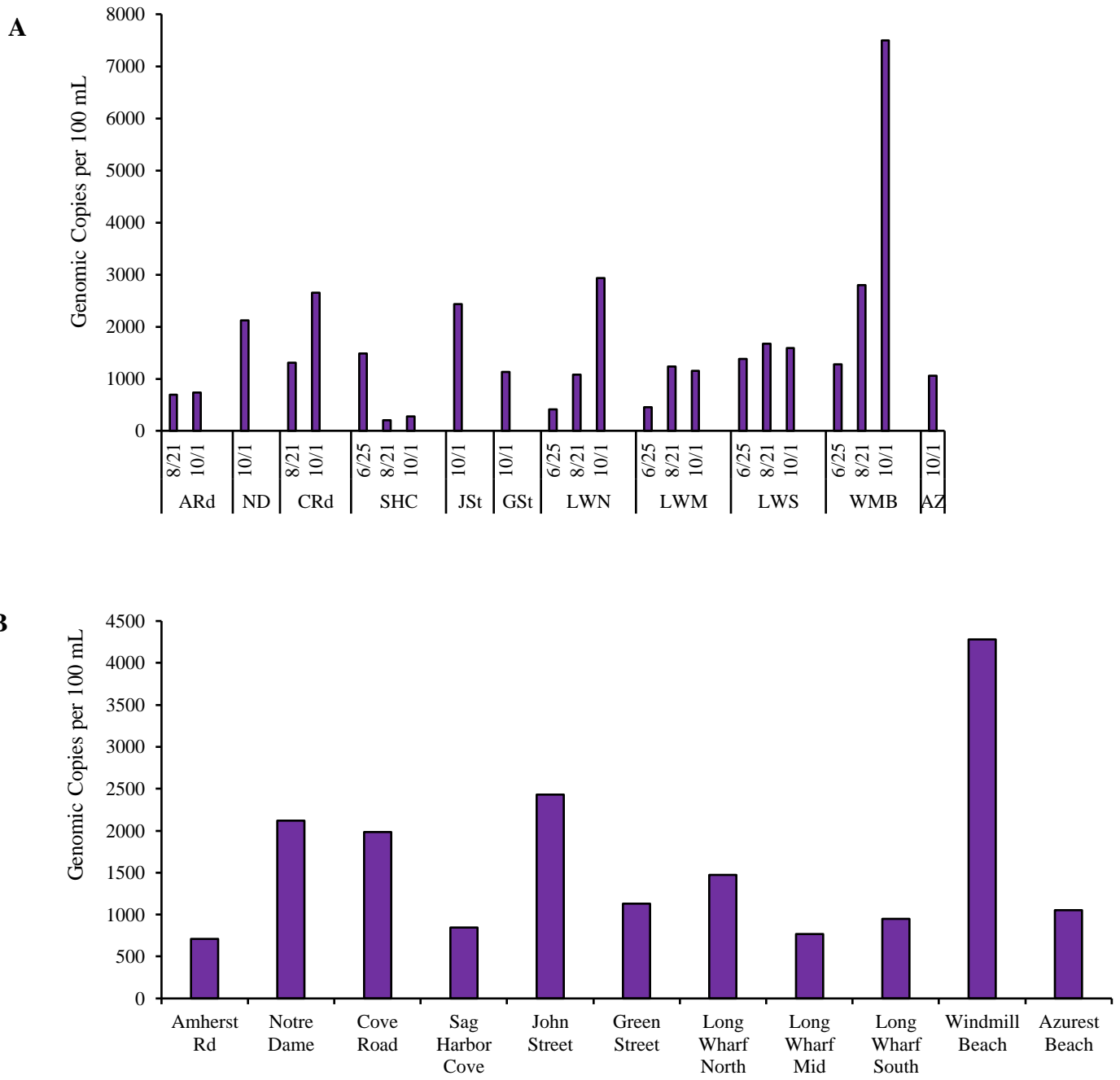


Figure 21. A.) Time-series, and B.) Summer averages of enterococcus concentrations (genomic copies per 100ml) across Haven’s Beach in Sag Harbor during 2024.

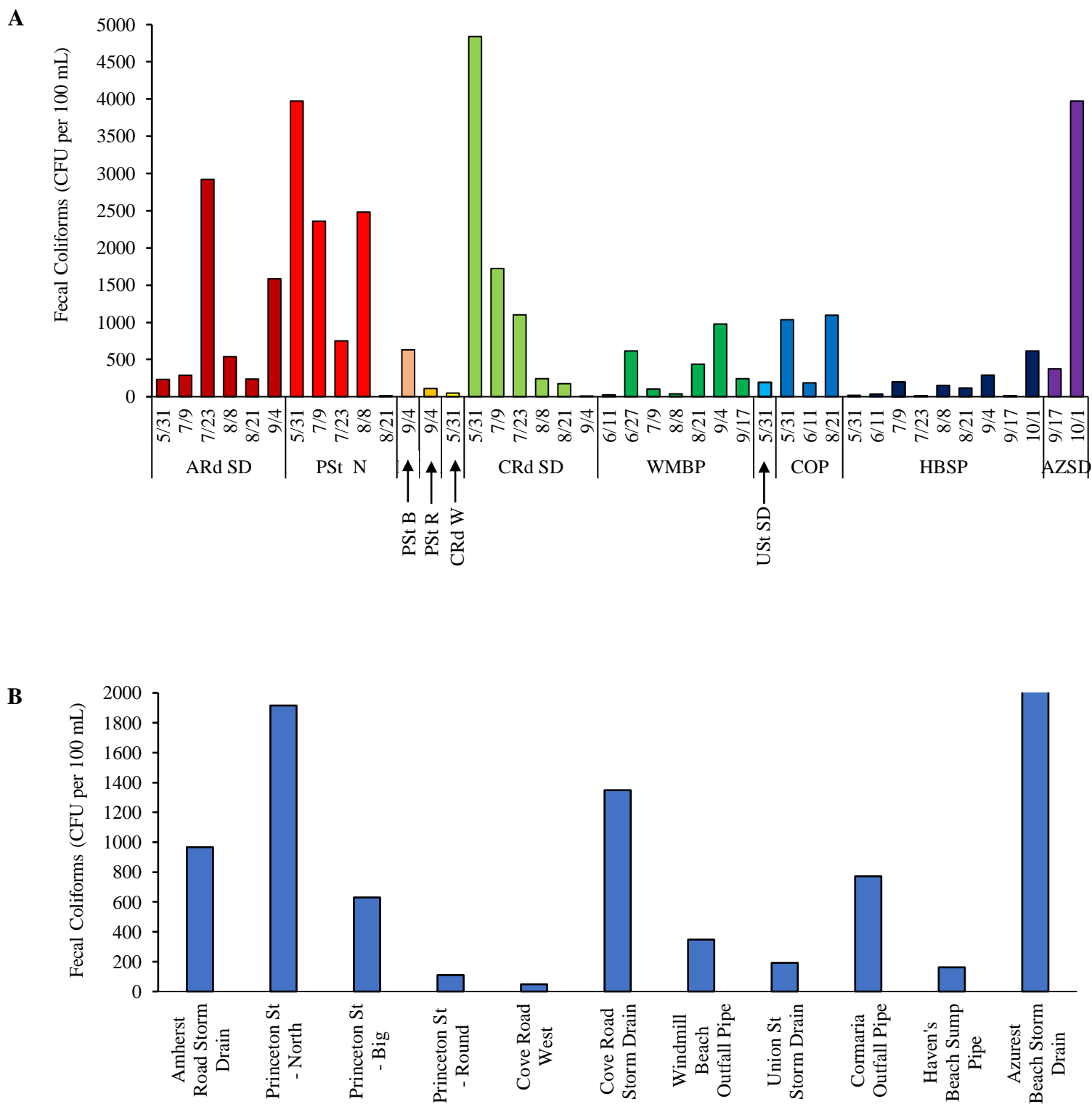


Figure 22. A.) Time-series, and B.) Average fecal coliform concentrations (CFU per 100 mL) across storm drains in Sag Harbor during 2024.

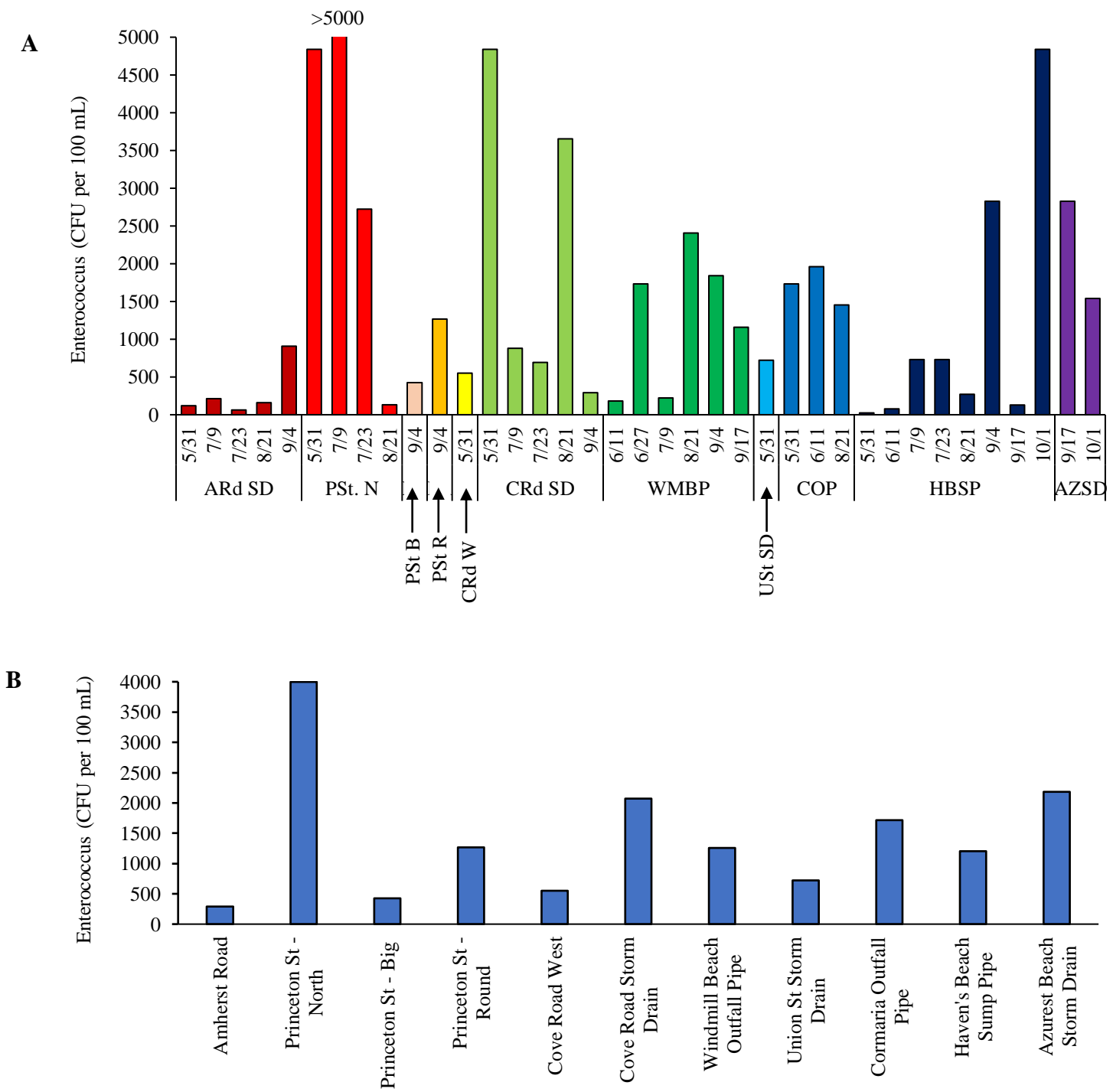


Figure 23. A.) Time-series, and B.) Average enterococcus concentrations (CFU per 100 mL) across storm drains in Sag Harbor during 2024.

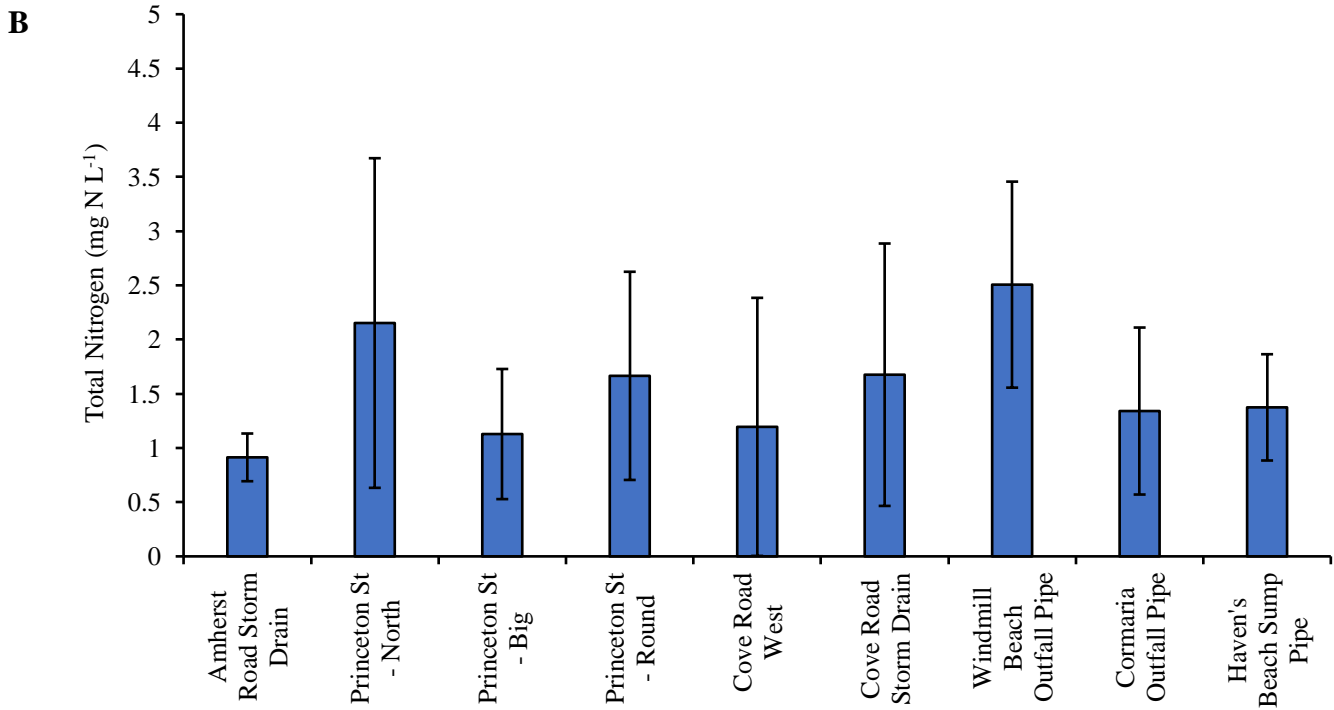
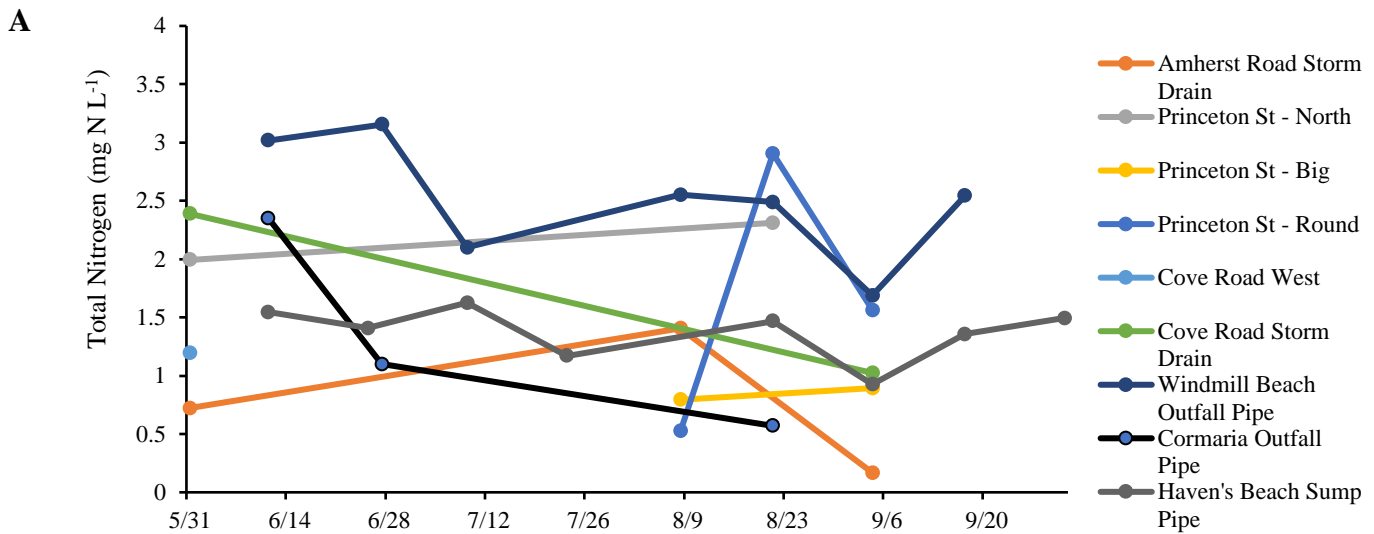


Figure 24. A.) Time-series, and B.) Summer average of total nitrogen levels (mg N/L) at storm drains in Sag Harbor during 2024. Columns represent means \pm standard error.