AVIAN and BENTHIC INVERTEBRATES

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Summary

The USGS Western Ecological Research Center, San Francisco Bay Estuary Field Station conducted one year of avian and benthic invertebrate pre-installation (Nov 2011 – April 2012), and two years of post-installation (September 2012 – April 2013 and September 2013 – April 2014) monitoring for the Living Shorelines Near-shore Linkages project. Our primary objective was to determine species and guild specific responses to restored habitat relative to control areas and pre-installation conditions using a Before-After Control-Impact (BACI) design. Both pre- and post-installation densities were highest at Eden Landing (EL) treatment and control sites where small shorebirds predominated. Wader species increased significantly post-installation in the treatment area at EL. At The Nature Conservancy (TNC), densities of Black Oystercatcher increased at treatment plots in comparison to pre- installation and control densities. Avian diversity and species richness was greater at TNC than EL for nearly all years and tide heights in both control and treatment areas. Both sites were used primarily for foraging at low tide, and non-foraging (resting, preening, etc.) behaviors at high tide. Benthic invertebrate density and community structure differed greatly between the two sites, with polychaetes dominating TNC and bivalves dominating EL. Density and biomass was substantially greater at EL. Preliminary analyses suggest that the treatments installed at TNC have positively influenced benthic invertebrate density, richness and biomass. The oyster treatments appeared to have a positive effect on amphipod density, while eelgrass treatments benefited polychaete density. While the treatment area at EL had higher density pre-installation, we observed a substantial increase in bivalves in the first post-installation sampling period. Our preliminary results suggest that some avian and invertebrate species may be responding to oyster and eelgrass habitat restoration; however, continued monitoring as these habitats will be important for understanding species responses to living shoreline restoration methodologies.

Introduction

The USGS Western Ecological Research Center, San Francisco Bay Estuary Field Station has monitored waterbird and benthic invertebrates at eelgrass and oyster enhancement sites for the Living Shorelines Near-shore Linkages project since November 2011. Our work helps to evaluate if the project is reaching its overall goal by addressing several project objectives, including: Objective 3 - determine the extent to which treatments enhance habitat for birds and benthic invertebrates relative to areas lacking structure and pre-treatment conditions; Objective 4 - determine if different types of treatments influence avian and invertebrate habitat value differently; Objective 5 - evaluate potential for subtidal restoration to enhance nearby intertidal mudflat by evaluating food resources; and Objective 7 - determine if position in the Bay influences establishment of habitat characteristics that attract birds and their benthic invertebrate prey.

Section 1: Methods

1.1. Overall Monitoring Design

Our study is focused on the winter as well as fall and spring migratory periods when several hundred thousand waterfowl and shorebirds rely on prey resources in the Bay to maintain adequate body condition and build reserves for reproduction. At the two project intertidal study sites located along the Hayward (Eden Landing North, ELN) and San Rafael (The Nature Conservancy, TNC) shorelines, we are evaluating species and guild specific responses to restored habitat relative to control areas and pre- installation conditions using a Before-After Control-Impact (BACI) design (Stewart-Oaten et al., 1986; Stewart-Oaten, 2003). Each paired treatment and control study area is subdivided into zones (Fig. 1) encompassing eelgrass and oyster treatment plots (zone B) as well as 150-m zones immediately inshore (zone A) and offshore (zone C) of the plots. This design allows us to measure potential avian and invertebrate responses both in the immediate vicinity of the treatment plots, as well as in adjacent areas that may be influenced by the enhancement treatments.

1.2. Avian Monitoring

1.2.1 Density, Relative Abundance, Diversity and Richness

During the pre-treatment (Year 0, Nov 2011 – Apr 2012) and two post-treatment periods (Year 1, Sep 2012 – Apr 2013; Year 2, Sep 2013 – Apr 2014), we conducted low tide and high tide surveys twice a month to monitor avian density and behavior at each site. Low tide surveys were conducted on a falling tide and started as soon as the mudflat started to expose at each site. As site elevations differed between sites, low tide counts began at 0.9-ft MLLW at TNC, and 3.0-ft MLLW at Eden Landing (EL) sites. At TNC, low tide surveys of each zone were conducted while the tideline was present in the zone to more accurately represent shorebird use of the site. High tide was considered 3.0-ft at TNC, and 3.5-ft at ELN. During each survey, trained observers used spotting scopes from a consistent observation point to count and identify to species all birds in each zone.

Relative abundance and density were summarized by species guild for TNC and ELN at high or low tide in the control or treatment area for each year of the study. Season was defined as: fall, Sep – Oct; winter, Nov – Jan; spring, Feb – Apr. Species diversity and richness were calculated for TNC and ELN at high or low tide in the control or treatment area for each year of the study (pre-treatment, year-1, and year-2). The Shannon Diversity Index was used to assess species diversity and was calculated as:

$$\text{Shannon Index } (H') = -\sum_{i=1}^{s} p_i \ln p_i$$

where p_i is the proportion (p) of individuals in the population belonging to a particular species (i). Species richness was calculated as the total number of species present at a given site, tide height, and treatment type for each year.

1.2.2 Behavioral Scans

After recording total numbers, we collected information on behavior of birds. Dissimilar conditions between sites required slightly different sampling methods at each. For high tide surveys at both sites and for low tide surveys at TNC, we used scan sampling and recorded the instantaneous behavior of 20% of all individuals of each species. At ELN during low tide, we recorded behavior and abundance simultaneously, as there were often far too many birds and not enough time for separate scans to be conducted. During scan surveys, the selected individual was observed for 10 seconds and the last behavior witnessed was recorded. Behaviors were categorized as follows: forage, swim/walk, sleep, rest, preen, social, drink, alert, and fly. Observed individuals were chosen at random by swinging the scope and observing the individual in the center of the field of view when the scope came to a stop. Behavioral scans were summarized as proportional behavior by species guild for TNC and ELN at high or low tide in the control or treatment area for each year of the study.

1.2.3 Focal Observations

We conducted focal observations of foraging individuals within each of 3 foraging guilds: benthivores, piscivores, herbivores. Each month, 10 randomly-selected birds (using the randomization methods previously described), from each target species within a guild were observed in both the treatment and control areas of TNC and ELN. Foraging birds were observed for 3 minutes (open water birds) to determine dive/pause durations, or 1 minute (shorebirds) to determine peck rates, both measures of foraging intensity. Other behaviors were recorded as probe, capture, walk, turn, run, flight, preen, social, rest, and sleep.

1.3. Benthic Invertebrate Monitoring

1.3.1 Benthic Invertebrate Cores

We collected pre- and post-installation benthic invertebrate samples at all study sites during fall and spring to evaluate how treatments may influence prey resources for migratory birds. Pre-installation samples were collected in December 2011 and May 2012, while post-installation samples were taken in September 2012, 2013, and in April 2013, 2014. At treatment and control areas within each study site, we took benthic cores (10-cm deep, 10-cm diameter) along four 500-m transects that ran perpendicular to shore (Fig. 1). Along each transect, two replicate samples were taken in each zone. In treatment areas, transects bisected planned treatment plots, and we collected cores in each of these plots. Cores were labeled to indicate sampling transect, zone and replicate (e.g. TNC01-B-1), refrigerated, and processed each within 72 hours of collection by rinsing them through 0.5-mm sieves and preserving all retained invertebrates in 70% ethanol with rose-bengal dye. Invertebrates were sorted, identified to lowest possible taxonomic class, enumerated, and measured (bivalves). All invertebrate technicians conformed to QA/QC procedures for a sorting efficiency > 90%. Ash-free dry weight (AFDW) was measured or calculated based on species size class to biomass transformations taken from the literature or previously determined at USGS. Invertebrate densities and dry biomass were summarized, and spatial distribution maps were created in ArcGIS by interpolating invertebrate biomass via Inverse Distance Weighting.

Section 2: Results and Discussion

2.1 Avian Monitoring

2.1.1 Densities, Diversity and Richness

Comparison of pre- and post-treatment surveys indicate that avian densities and guilds differ greatly between TNC and ELN sites. At ELN the prevalence of large flocks of medium and small shorebirds resulted in greater mean density (> 200 birds/ha) and overall relative abundance than at TNC. During high tide, both TNC and ELN were characterized by low mean densities (< 20 birds/ha) consisting predominantly of diving ducks. Diversity and species richness of waterbirds was greater at TNC than at ELN for nearly all years and tide heights in both control and treatment areas (Table 1). The greatest diversity (H´ = 2.41) and richness (32 species) were observed at TNC at low tide in year-2 in the treatment area, which grew in diversity each year. While ELN was lesser than TNC in both measures, it increased in richness at low tide from pre-treatment to post-treatment years. At both sites, diversity and richness were lesser at high tide than at low tide.

2.1.1.1 San Rafael/TNC

At TNC during low tide, overall mean densities of birds increased inshore (zone A) of oyster and eelgrass plots, and remained similar in the vicinity (zone B) and offshore (zone C) of the plots (Fig. 2). Avian densities were higher in zone A compared to the other zones at TNC. Due to the steep gradient of this site, zones B and C were rarely fully exposed during low tide and therefore generally were unsuitable foraging habitat for shorebirds. During low tide, total mean density of birds remained similar throughout all three years of study in each zone, including inshore of oyster and eelgrass plots (zone A), in the vicinity (zone B) and offshore (zone C). A small increase in density in the treatment area in zone A from pre-treatment to post-treatment years was observed, while slightly higher densities were consistently exhibited in the control area versus the treatment in zone A (Fig. 2).

In zone B, increased abundance of several species was observed between years, including Black Oystercatcher (*Haematopus bachmani*) and Forster's Tern (*Sterna forsteri*; Fig. 3). Neither of these species was observed in this area prior to treatment installations, but were present on oyster elements in year-1 and year-2. Additionally, several guilds, including wading birds (such as Great Egrets, *Ardea alba*, and Snowy Egrets, *Egretta thula*), dabbling ducks, and medium shorebirds were observed on or near the oyster elements in zone B at TNC (Fig. 4). Densities of gulls in zone B also increased slightly each year. Dabbling ducks and medium shorebirds were not observed in zone B until year-2. Dabbling duck densities decreased or remained similar in the control, and increased in the treatment (Fig. 5). Wading birds did not use zone B pre-treatment, but were using this area in both treatment years, where density decreased in the control and increased in the treatment from year-1 to year-2.

Mean relative density differed between winter and spring, particularly in zone A at low tide (Fig. 6). In winter months at low tide, zone A was proportionally dominated by small shorebirds in the control area throughout the study, though medium shorebirds and diving ducks increased in proportion in the treatment area. Comparatively, spring months in zone A at low tide was characterized by a larger proportion of diving ducks and fewer shorebirds. At high tide there was little difference between relative densities of species guilds in winter or spring.

During high tide, overall mean densities of birds remained similar throughout all three years of study in each zone at TNC, with a slight decrease in density in the control area in zone B from pre-treatment to year-1, and a similar increase in year-2 (Fig 7). Mean density also decreased slightly in the control in zone C from pre- to post-treatment years.

At low tide, the control area at TNC was consistently high in diversity and richness throughout the study (Table 1). However, the treatment area showed a marked increase in diversity and richness from pre-treatment to year-2, although Buffleheads were consistently the most relatively abundant species (27 – 43%).

At high tide, TNC was consistently dominated by diving ducks in both the control and treatment areas in all years (Table 1). The control area maintained a consistent level of diversity and richness. However, there was a decline in diversity and richness in the treatment area from pre-treatment to year-2. Bufflehead remained a dominant species in the treatment areaand increased in relative abundance from pre-treatment (28%) to year-2 (46%).

2.1.1.2 Hayward/Eden Landing

Avian density at ELN was driven predominately by shorebirds in zones B and C of both the treatment and control areas. Overall density declined post- installation, though it remained constant from year-1 to year-2 (Fig 8). As treatment and control areas have similar density trends, it is unlikely that the decline is related to the test elements installed at this site. Rather, the consistent decline in density may be a consequence of the deepening channel at the mouth of Mt. Eden Creek to the south of the study area. Another explanation could be increased availability of low-tide habitat in adjacent recently-restored managed ponds. Densities of wading birds, however, increased at ELN treatment plots in comparison to pre-treatment and control, and between year-1 and year-2 in the fall in zone B treatment (Fig. 9), potentially indicating increased resources for these species.

During high tide, overall bird densities have remained consistently low throughout the three years of study (Fig. 10). Diving and dabbling ducks are the most abundant species observed at this site. Densities have been consistently higher in the treatment area than in the control since the pre-treatment year, indicating that this trend is likely due to factors aside from the treatment installations, such as depth.

Relative density at ELN varied more by tide height than by season (Fig. 11). At low tide, regardless of season, ELN was characterized by proportionally dominant small shorebirds in zones A and B, and medium shorebirds in zone C. However, at high tide, shorebirds were nearly absent and diving ducks were the most relatively dense guild, particularly in zones B and C.

The lowest diversity and richness observed throughout the study was during high tide at ELN (Table 1). The treatment area of ELN was strongly dominated by scaup every year (70 – 93%), which resulted in low diversity and richness. Though more diverse than the treatment area, as much as 80% of birds in the ELN control area at high tide were scaup.

At low tide, diversity and richness were highest in year-1. The treatment area in year-1 had the greatest richness observed at the site during any year or tide height in either area. In year-1, the diversity was also the highest seen in the treatment area throughout the study. In every year, Western Sandpiper was the most relatively abundant species at low tide in both the control (40 – 50%), as well as the treatment (38 – 62%) area.

2.1.2 Behavioral Scans

Behavior at both TNC and ELN varied from high to low tide. At both sites, birds were predominantly foraging at low tide, particularly at ELN. As surveys indicated, ELN is used by large flocks of shorebirds at low tide, and scans indicate that they used the site for foraging in both control and treatment areas. At high tides, however, both locations were used predominantly for non-foraging behaviors, such as resting or sleeping.

2.1.2.1 San Rafael/TNC

Behavioral diversity at TNC at low tide was limited in pre-treatment and control and treatment areas were not equally represented by all guilds (Fig. 12). The control area was predominantly used for foraging (dabblers = 75% and divers = 68%), while divers were the only group to use the treatment area for foraging (53%). Divers also used the treatment area for preen/comfort behaviors (32%). No grebes were observed in the control area, no dabblers were observed in the treatment area, and medium shorebirds were not observed in either area. Gulls (control and treatment) and grebes (treatment only) were exclusively observed swimming/walking.

For most guilds, low-tide behavior diversified in year-1, though foraging remained the most dominant use throughout the study area and increased from pre-treatment (Fig. 12). Dabblers used the site 100% for foraging (control and treatment). The proportion of divers using the area for foraging was reduced from pre-treatment. Though foraging remained their primary behavior in the treatment area (49%), divers used the control area primarily for resting (38%). Grebes behavior diversified from pre-treatment in both the control (25% each of forage, swim, sleep, other) and treatment (33% each of swim, preen/comfort, other) areas, with no dominant behavior. Gull behavior also diversified from pre-treatment and they used both the control and treatment primarily for resting (67% and 40%, respectively), compared exclusively with swimming/walking in pre-treatment. In year-1, medium shorebirds observed in the control area were exclusively using the area for foraging.

Year-2 was strongly dominated by increased foraging behavior at low tide in both the control and treatment areas across nearly all guilds (Fig. 12). Foraging of diving ducks in the control area increased from 26% in year-1 to 49% in year-2. In the treatment area, diving ducks increased their foraging rate from 49% in year-1 to 78% year-2. Grebes were the only guild which did not display an increase in foraging from previous years, and instead saw an increase in swimming/walking behavior in both areas (control = 67%; treatment = 100%). Though medium shorebirds were not observed in the control, there was a 100% increase in foraging observed in the treatment area from all previous years.

Similar to observations at low tide, the behavioral diversity of surveys in pre-treatment at high tide at TNC was limited, and control and treatment areas were not equally represented by all guilds (Fig. 13). Divers and grebes used the control area primarily for sleeping (66%). Grebes also used the treatment area primarily for sleeping (42%). The treatment area was used by divers for foraging (50%) and sleeping (39%). The “Other” guild (e.g. cormorants, eared/horned grebes) used the control and treatment areas exclusively for foraging. No dabblers or gulls were observed in either area.

As with pre-treatment, not all guilds were equally represented in year-1 at high tide in control and treatment areas (Fig. 13). Year-1 was dominated by resting behavior, but an increase in behavioral diversity was observed. Foraging behavior of divers increased marginally, from 21% in pre-treatment to 31% in year-1 in the control, and from 50% to 54% in the treatment area. While no grebes were observed foraging in the control area in pre-treatment, 17% of grebes were foraging in year-1. Grebes primarily used the control area for resting and sleeping. Foraging of grebes in the treatment area increased from 25% in pre-treatment to 50% in year-1. Dabbling ducks were only observed resting in the control area and not observed in the treatment area. Gulls and others were observed primarily resting in the treatment area.

We observed an increase in high tide foraging during year-2 at TNC (Fig. 13). The proportion of divers foraging and sleeping in both control and treatment areas was consistent from year-1 to year-2. Compared with pre-treatment, however, birds used the site less often for sleeping and were engaged in a greater diversity of behaviors. Proportionally fewer grebes were observed foraging in both the control and treatment areas in year-2 than in year-1, though the foraging rates in the treatment area were similar to those observed in pre-treatment. For the first time, gulls were observed foraging in both the control and treatment areas, although resting was their primary behavior. As with pre-treatment, “Other” birds were observed foraging in the control (100%) and treatment (20%) areas, though resting was the dominant behavior in the treatment area.

Three guilds (dabblers, divers, and gulls) showed an increase in foraging behavior in the treatment area from pre-treatment to year-2 at low tide. No dabblers were observed in the treatment area in pre-treatment but foraged in the control, so it is possible that the presence and increase in foraging in year-1 and -2 could be attributed to the treatment. A similar increase was not observed at high tide, which may indicate that the depth of the site at high tide made the site unattractive to dabblers for foraging or non-foraging behaviors.

The proportion of divers foraging at high tide remained consistent throughout the study. However, at low tide, proportionally more divers were foraging in the treatment area in year-2 than they were pre-treatment, while there was no change in the control area during that same time. This indicates that the treatment may have provided improved foraging habitat for diving ducks at low tide.

2.1.2.2 Eden Landing/ELN

In pre-treatment at low tide, foraging was the primary behavior across all guilds observed at ELN (Fig. 14). Nearly 100% of all dabblers, divers, gulls, and small shorebirds were foraging in both the control and treatment areas. Medium shorebirds also predominately foraged, but a small proportion (9%) rested in the control area. No grebes were observed at the site at low tide, and diving ducks were only observed in the control area.

Behavior at low tide was more diversified in year-1 than what was observed in pre-treatment (Fig. 14). Though foraging was still observed, a greater proportion of dabbling ducks were swimming/walking in both the control (44%) and treatment (58%) areas. While still using both areas for foraging, gull behavior in both areas in year-1 was predominantly resting (control = 62%; treatment = 60%). Greater than 90% of medium and small shorebirds foraged in both control and treatment areas. Grebes were only observed in the control area and were exclusively swimming/walking.

By year-2, foraging was again the most common behavior at low tide and foraging rate increased from year-1 in every group that had previously used the site for foraging (Fig. 14). In year-1, dabbling ducks foraged less than 24% of the time in the control or treatment areas. By year-2, foraging had increased to 93% in the control, and 66% in the treatment area. Medium and small shorebird behavior remained consistent from pre-treatment, predominantly foraging in both areas. In year-2, gulls used the treatment and control areas more for non-foraging behaviors (resting and preen/comfort) than in all previous years. Diving ducks and grebes were observed swimming/walking in the treatment area, but were not observed in the control.

Behavior was diverse during at high tide at ELN in pre-treatment, though not all guilds were equally represented in both control and treatment areas (Fig. 15). Dabbling ducks used the control area for swimming, while the treatment was used for foraging and sleeping. Diving ducks primarily used the control area for foraging (72%), and the treatment area nearly equally for foraging (32%) and swimming (36%). Grebes split their use of the control area equally between foraging and resting. They primarily used the treatment area for swimming. “Other” birds were observed swimming/walking in the control area, but not in the treatment. No gull behavior was observed at the site.

Year-1 at high tide at ELN continued to be behaviorally diverse, but behaviors were not consistent with pre-treatment observations (Fig. 15). Dabbling ducks used the control for foraging (33%) and resting (66%) as opposed to swimming in pre-treatment. Conversely, in year-1, they used the treatment area exclusively for swimming while behavior was diverse in that area the previous year. Diving duck behavior in the control diversified, though while the percentage of foraging divers declined, foraging remained the most dominant in the control area (48%). In the treatment area, diving duck foraging behavior was consistent with pre-treatment, though there was a small reduction in sleeping and increase in swimming. Grebe behavior in the control was totally different from pre-treatment. Where pre-treatment was exclusively foraging and resting, year-1 was equally split between preen/comfort and swimming. Similarly, behavior of "other" birds observed in the control was entirely different from the previous year, shifting from swimming in pre-treatment to an equal split of foraging and "other" behaviors. Gulls were observed only swimming in the control area, but no gull behavior was observed in the treatment area.

By year-2, fewer guilds were represented, though foraging appeared more dominant than in previous years (Fig. 15). No dabbling ducks were observed in the control area, and their use of the treatment was primarily for resting. They did not forage in the treatment area. Diving ducks foraged in both the control and treatment areas, although in lesser proportion in both areas than in all previous years. They used both areas primarily for swimming and non-foraging behaviors. The use of both areas by grebes again changed from both previous years. Grebes used the control area exclusively for foraging, while the treatment was used for a diversity of behaviors—primarily swimming or sleeping. "Other" birds increased foraging rate to 100% in the control area and were not observed in the treatment.

Eden Landing North displayed a greater diversity of behavior at high tide than was observed at low tide, although foraging was far more prevalent at low tide throughout the study. As a more shallow location than TNC, it is not surprising that medium and small shorebirds forage at the site at low tide. As the site became inundated with the tide, shorebirds were not observed, indicating the area was unsuitable habitat for shorebirds for any behavioral needs. Conversely, divers and grebes were consistently observed foraging at high tide, but were not consistently present at low tide. The absence of divers and grebes at high tide and the presence of shorebirds at low tide indicate a strong tidal gradient to the site. This gradient may more strongly effect behavior than the treatment itself, as no clear trends in increased foraging activity in the treatment area is indicated by the data.

2.1.3 Behavioral Focal Observations

2.1.3.1 TNC and ELN

Complete results from focal observations at TNC and ELN are not yet available; however, because Black Oystercatchers have increased use of the TNC treatment area from pre- to post-treatment, those data were examined for a closer look at Black Oystercatcher energetic expenditure at the site. Prior to installation, there were no oystercatchers observed at the site in any zone or tide height. Results of focal observations indicate that while in treatment zone B, Black Oystercatchers at TNC spend 44% of their time engaged in foraging-related behaviors (probing, pecking, and capturing prey; Fig. 16). This suggests that the treatment installations may be providing a new and potentially valuable prey resource for this species.

2.2 Benthic Invertebrate Monitoring

2.2.1 Densities and Biomass

Benthic invertebrate density and community structure differed greatly between the two sites, with polychaetes dominating TNC and bivalves dominating ELN. Both invertebrate density and biomass were greater at ELN. Preliminary analyses suggest that the treatments installed at TNC have positively influenced benthic invertebrate density and biomass. The treatment area at ELN had higher invertebrate densities during all sampling periods, suggesting the site may have environmental conditions preferable to a benthic invertebrate community.

2.2.1.1 San Rafael/TNC

Benthic invertebrate density and biomass were highly variable between sampling periods at both the treatment (north) and the control areas (south) of TNC. Overall, mean invertebrate density was greater within the treatment area ($\bar{x}$=2,900/m^2) compared to the control area ($\bar{x}$=2,700/m^2). The lowest density was observed during the first sampling period in late fall 2011 ($\bar{x}$=850/m^2), while the greatest density occurred in fall 2012 ($\bar{x}$=3,800/m^2), with the treatment site having higher density ($\bar{x}$=4,200/m^2) than compared to the control site ($\bar{x}$=3,400/m^2).

Within zone B, density between treatment and control areas was highly variable throughout the sampling period (Fig. 17). Post-installation, treatments appear to have a positive effect on benthic invertebrate density, as density within zone B was higher in the treatment area than the control area in all time periods with the exception of spring 2013 (Fig. 17). The most notable effect of treatment on benthic invertebrate density occurred in the two most recent sampling periods, spring 2014 (treatment: $\bar{x}$=4,560/m^2; control: $\bar{x}$=2,480/m^2) and fall 2013 (treatment: $\bar{x}$=1,910/m^2; control: $\bar{x}$=1,180/m^2). Amphipods were the most abundant taxa group and were more abundant within the treatment site after installation (treatment: $\bar{x}$=2,180/m^2; control: $\bar{x}$=1,860/m^2), as were polychaetes (treatment: $\bar{x}$=290/m^2; control: $\bar{x}$=250/m^2) and oligochaetes (treatment: $\bar{x}$=120/m^2; control: $\bar{x}$=50/m^2). Cumaceans had relatively consistent densities between treatment and control areas (treatment: $\bar{x}$=145/m^2; control: $\bar{x}$=150/m^2). Bivalves were present at the site, however in relatively low densities (treatment: $\bar{x}$=13/m^2; control: $\bar{x}$=24/m^2).

Several treatments showed an increase in density from year-0 (spring 2012) to year-2 (spring 2014), most notably the oyster only treatment (Fig. 18). The same result was observed in the eelgrass test plot and eelgrass + oyster treatments. These overall trends were largely attributed to the most dominant taxa, amphipods. Polychaete density increased from year-0 to year-2 in the eelgrass only (year-0: $\bar{x}$=255/m^2; year-2: $\bar{x}$=510/m^2) and eelgrass test plot treatments (year-0: $\bar{x}$=130/m^2; year-2: $\bar{x}$=380/m^2), suggesting a positive effect of eelgrass presence. The plot control in zone B within the treatment area had high densities in year-0, which plummeted in year-1 and steadily increased in year-2 (Fig. 18).

Benthic invertebrate ash-free dry weight (AFDW) varied significantly by sampling period and control vs. treatment sites (Fig. 19). Total AFDW in both pre-installation sampling periods (late fall 2011 and spring 2012) and the first post-installation sampling period (fall 2012) was relatively low. Biomass increased by spring 2013, and remained consistently high in the last three sampling periods. In the spring 2013 and 2014 sampling periods, biomass was significantly higher in the treatment area compared with the control area, while the two areas were relatively even in the fall 2013 sampling period (Fig. 19; 20). Polychaetes comprised the majority of ash free dry weight at TNC, and 83% of total polychaete biomass is attributed to a single species, the bamboo worm, *Sabaco elongatus*. Additionally, the presence of a single gastropod, *Philine auriformis*, detected on the treatment area in spring 2013 contributed significantly to the biomass during that time period.

2.2.1.2 Hayward/Eden Landing

The benthic invertebrate community at ELN was dominated by bivalves and did not vary significantly between sampling seasons (Fig. 21). The treatment area harbored a greater density of benthic invertebrates in all four sampling periods (late fall 2011, spring 2012, fall 2012 and spring 2013). Pre-installation treatment area densities were higher than control areas, and the large increase in bivalve density in the post-installation period (fall 2012) may suggest that the treatment installations were placed in a location that fostered a greater growth of the population. Several bivalve species were present including *Corbula amurensis*, *Macoma petalum* and *Theora lubrica*, however *Gemma gemma* was the dominant bivalve taxa, comprising 99% of all bivalves. Polychaetes were the second most abundant taxa at ELN and were primarily comprised of a small sedentary species, *Streblospio benedcti* ($\bar{x}$=1,270/m^2), followed by two large errant polychaetes, *Neanthes succinea* ($\bar{x}$=285/m^2) and *Eteone lighti* ($\bar{x}$=265/m^2).

Ash-free dry weight at ELN showed similar patterns to density, with bivalves being the primary contribution. Additionally, the treatment area had a greater biomass than the control area during all sampling periods (Fig. 22), and most notably in the first post-installation treatment period, fall 2012 (Fig. 23). Biomass was concentrated in zone A, closest to shore in the shallow mudflat in all sampling periods, except fall 2012 where biomass was concentrated in the treatment area of zone B (Fig. 23).

2.2.2 Diversity and Richness

Benthic invertebrate diversity and taxonomic richness structure varied between the two sites, although both sites were dominated by a single taxa. Taxonomic richness and diversity was slightly higher at EL with a range of between 12 and 16 unique taxa per sampling period, and between 5 and 15 at TNC. Richness within treatments at TNC was higher than controls, and minimal variation was detected at ELN between treatments and controls.

2.2.2.1 San Rafael/TNC

In general, species richness was higher in treatment plots than in control plots and the highest number of taxa were found in the fall 2012 and spring 2014 (Table 2). Species evenness was low; Amphipoda were the most abundant, with *Ampelisca abdita* and *Monocorophium* spp. comprising the majority of all individuals recorded during the study. We detected a total of four amphipod species in 4 families and all were present in both control and treatment areas. A total of nine species in ten families of polychaetes were recorded at the site over the course of the study period. Six species were detected in the treatment site, while only four were found in the control area.

2.2.2.2 Hayward/Eden Landing

At Eden Landing, species richness remained relatively high throughout both areas over the course of study period. Taxonomic richness increased slightly in the treatments, post-installation, with the highest number of taxa (x=16) found in the treatment plots in the fall 2012 and spring 2013 (Table 3). Species evenness was low with *Gemma gemma* being the most abundance species present, comprising 82% of all individuals detected during the study. Bivalve species richness was similar with four species recorded in the treatments and three species in the control areas. Amphipod species richness appeared to be even between control and treatment areas, however varied based on sampling season. In fall 2012, three species were detected in the treatment area, while two species were detected in the control area. However in the previous sampling period, spring 2012, amphipods went completely undetected.

2.2.3 Prey energetic value and size class: implications for foraging birds

2.2.3.1 San Rafael/TNC

While amphipods were the most abundant taxa at TNC, preliminary data analyses suggest that polychaetes are the most significant component to total macroinvertebrate AFDW at the site (Fig 19). Several studies have shown that foraging shorebirds are capable of ingesting large polychaetes, and in some cases polychaetes have been identified as the most important diet item (Iwamatsu et al. 2007). Total macroinvertebrate AFDW increased in treatment plots during the last three sampling periods, suggesting that treatments may have played a role in increasing energetic value of the area for foraging waterbirds and other predators (Fig 19).

2.2.3.2 Hayward/Eden Landing

Overall, the mudflat at ELN contains greater density and biomass of potential prey items for foraging waterbirds in comparison to TNC. The peak total AFDW for the site (35 g/m²) was sampled in the treatment area during fall 2012 (Figs 22 and 23), shortly after test treatments were installed at the site. The bulk of biomass during this time period was in zone B, suggesting that the treatments may have had a positive effect on invertebrate density and biomass. Bivalves were the primary source of available prey biomass at the site during all sampling periods (Fig 22), with the gem clam (*Gemma gemma*) representing 65.5% of total bivalve biomass (Fig 24). Of all bivalves recorded in zone B, 99.8% were within consumable size limits (< 6mm) for small shorebirds as well as for larger benthic foraging birds.

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Stewart-Oaten A., Murdoch W. W. & Parker K. R. (1986) Environmental Impact Assessment: “Pseudoreplication” in time? *Ecology* **67:** 929–940

Figures and Tables

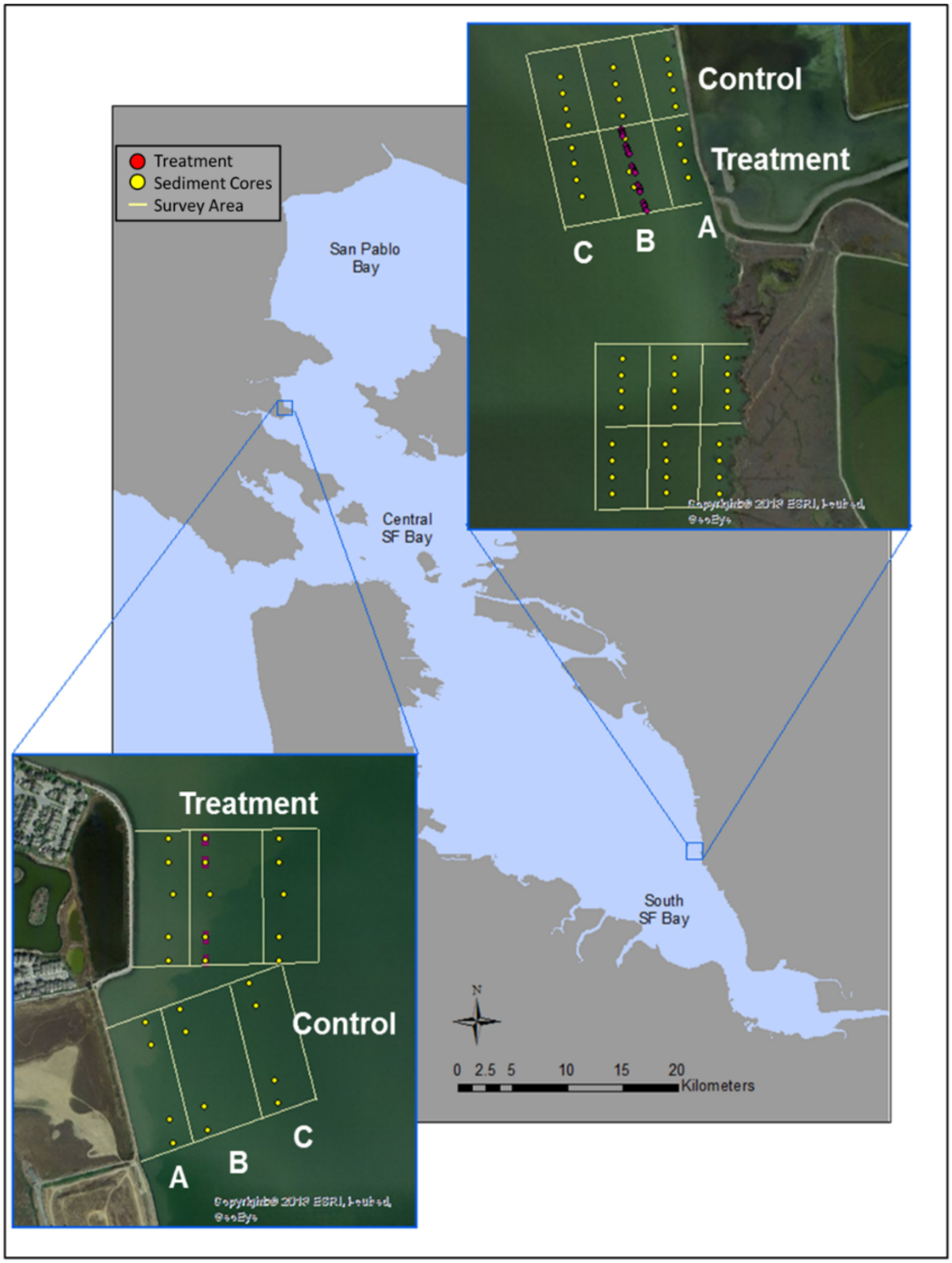

Figure 1. The Nature Conservancy in Central San Francisco Bay and Hayward/Eden Landing study locations in South San Francisco Bay, with treatment and control plots broken into three survey zones; inshore (A), central (B), and offshore (C), with sediment coring locations (yellow circles), and treatment locations (red circles).

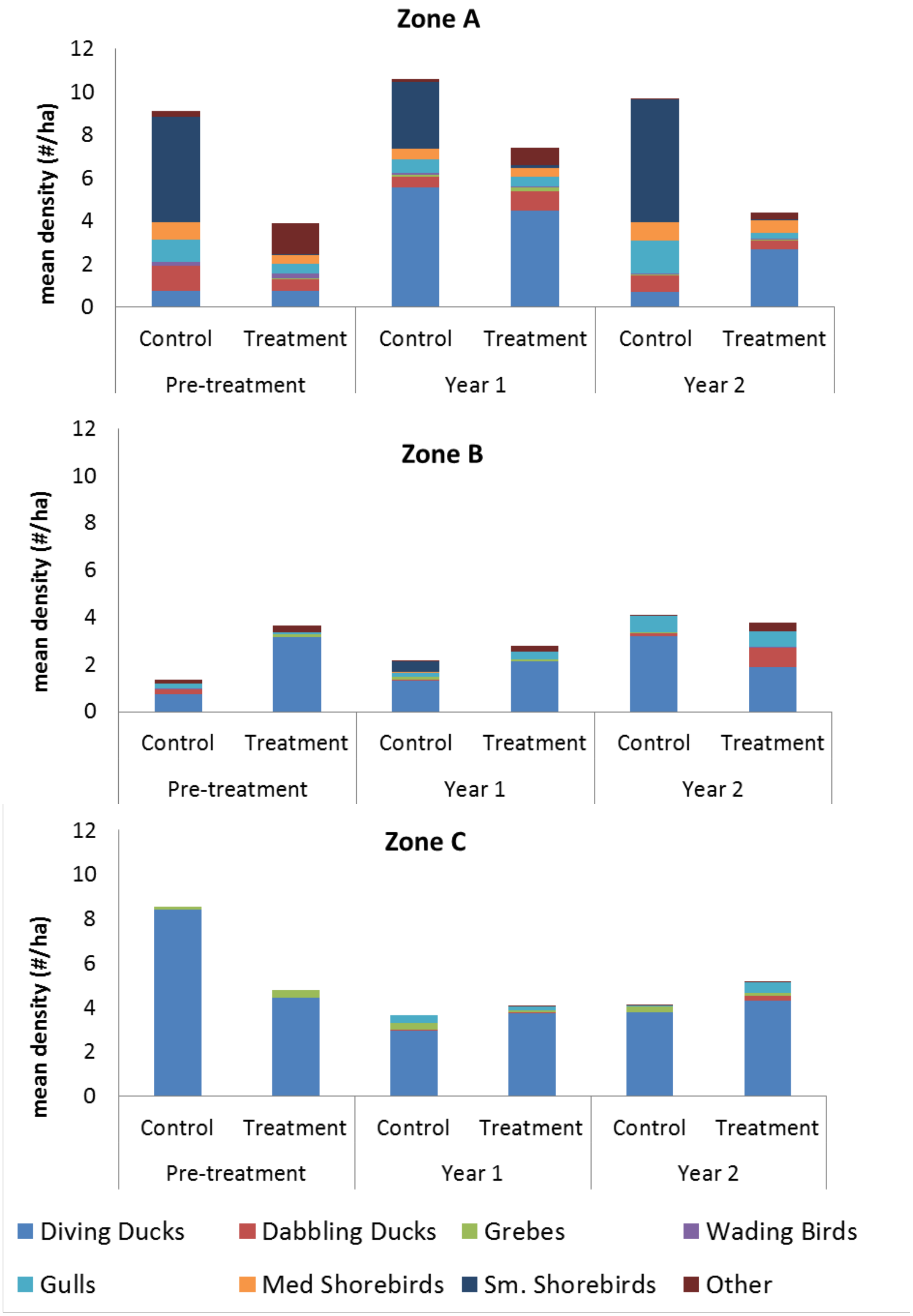

Figure 2. Total mean density of all avian guilds during low tide at The Nature Conservancy (TNC) in treatment and control areas during each of the three years of study. Fall (Sept. and October) data were excluded, as surveys were not conducted during this period in the "pre-treatment" year.

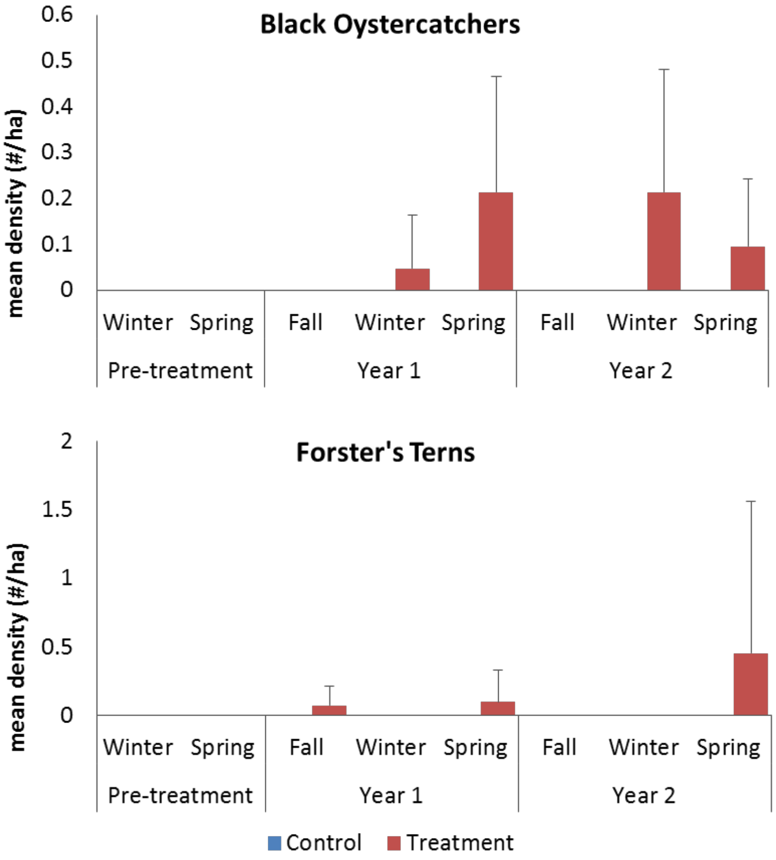

Figure 3. Mean seasonal density of black oystercatchers and Forster's terns in zone B at low tide at TNC among pre-treatment and post-treatment years. No surveys were conducted during fall of the pre-treatment year. Note: y-axis differs between graphs.

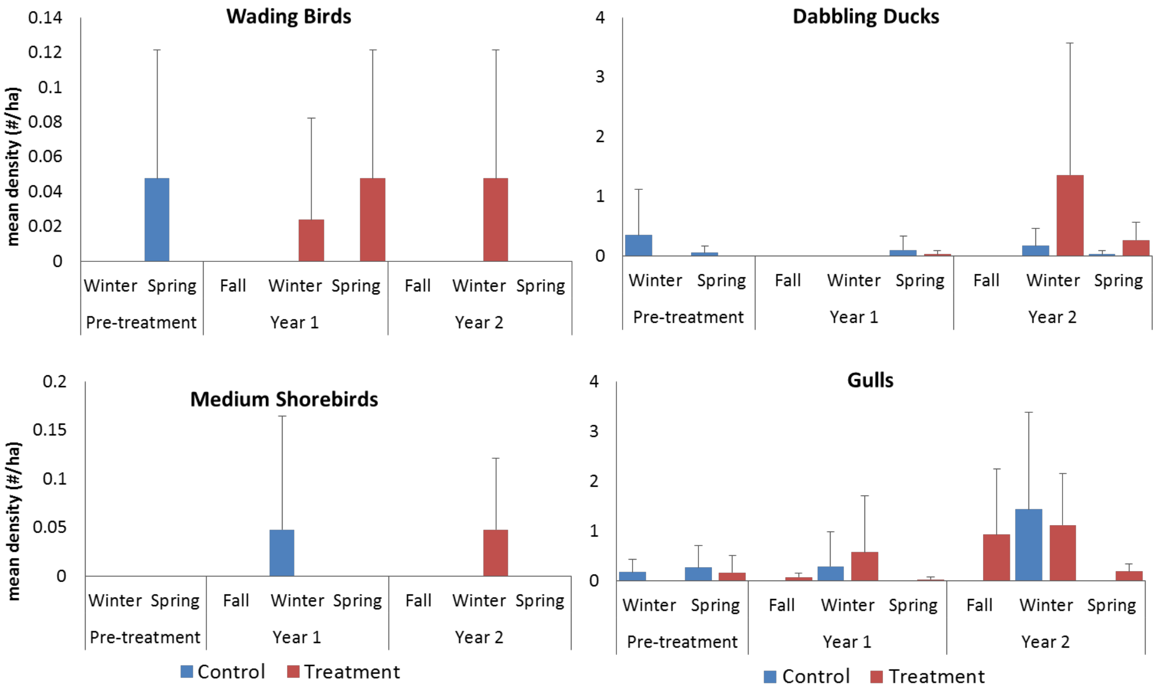

Figure 4. Mean seasonal density (±SD) of wading birds, dabbling ducks, medium shorebirds, and gulls in zone B of the control and treatment areas during low tide at TNC among pre-treatment and post-treatment years. Note: y-axis scale differs among guilds.

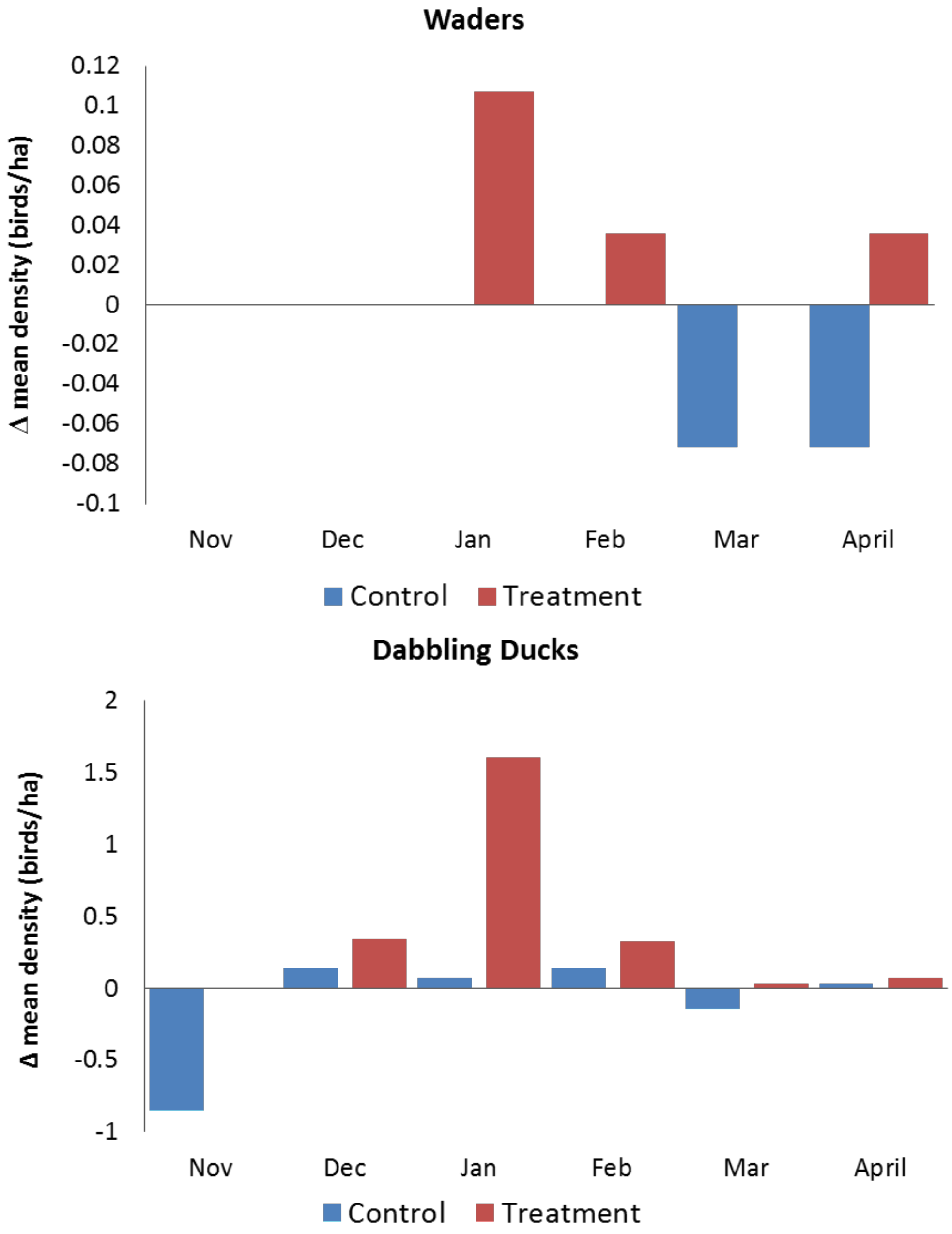

Figure 5. Mean monthly change density between pre- and post-treatment years in zone B of the control and treatment plots at TNC.

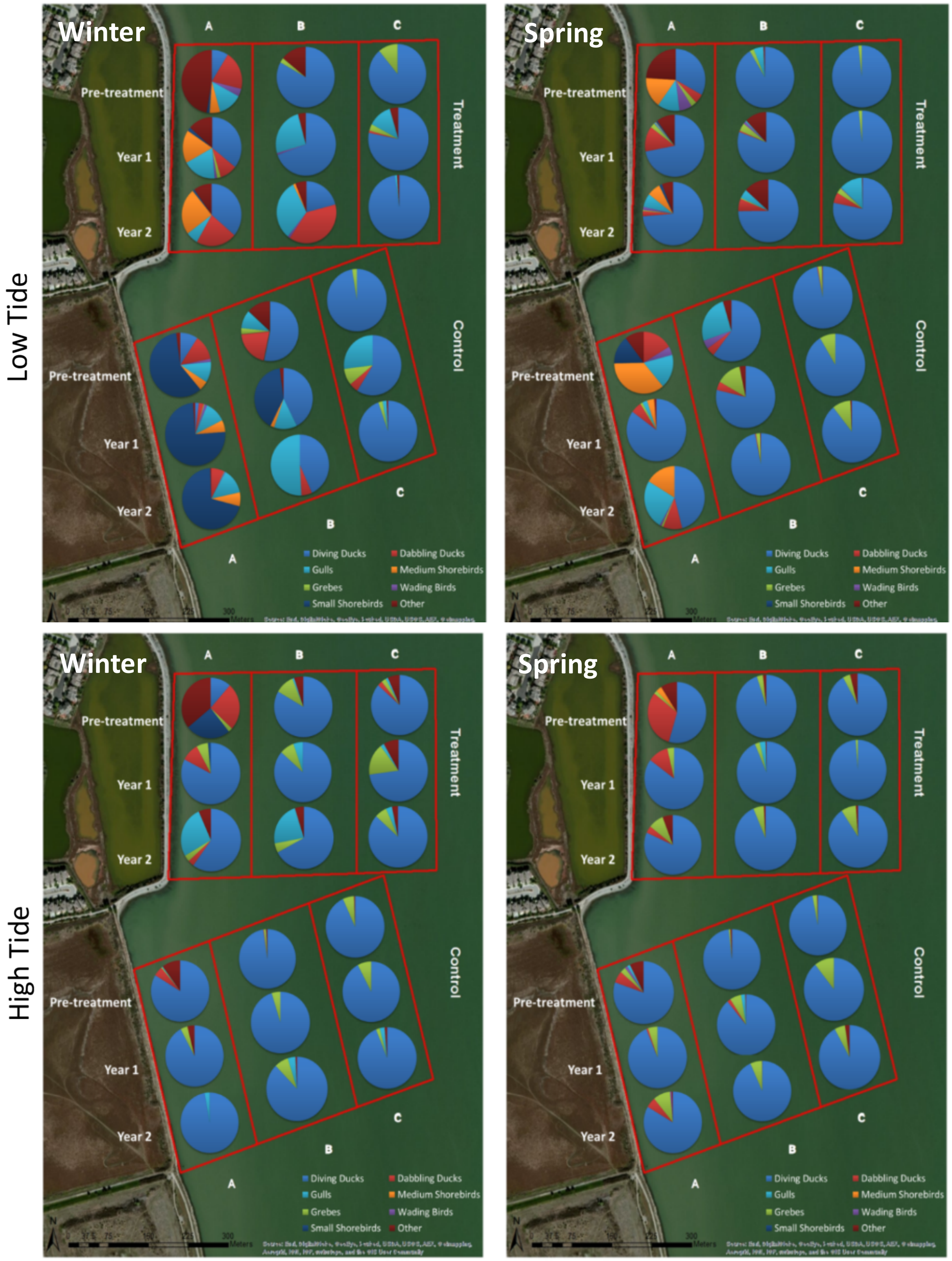

Figure 6. Mean relative density avian guilds in each survey zone (A, B, and C) of treatment (top) and control (bottom) areas during low tide (top two panels) and high tide (bottom two panels) in winter (left) and spring (right) at TNC. Charts in zones of each area represent pre-treatment (top rows) and treatment year-1 (middle rows) and year-2 (bottom rows).

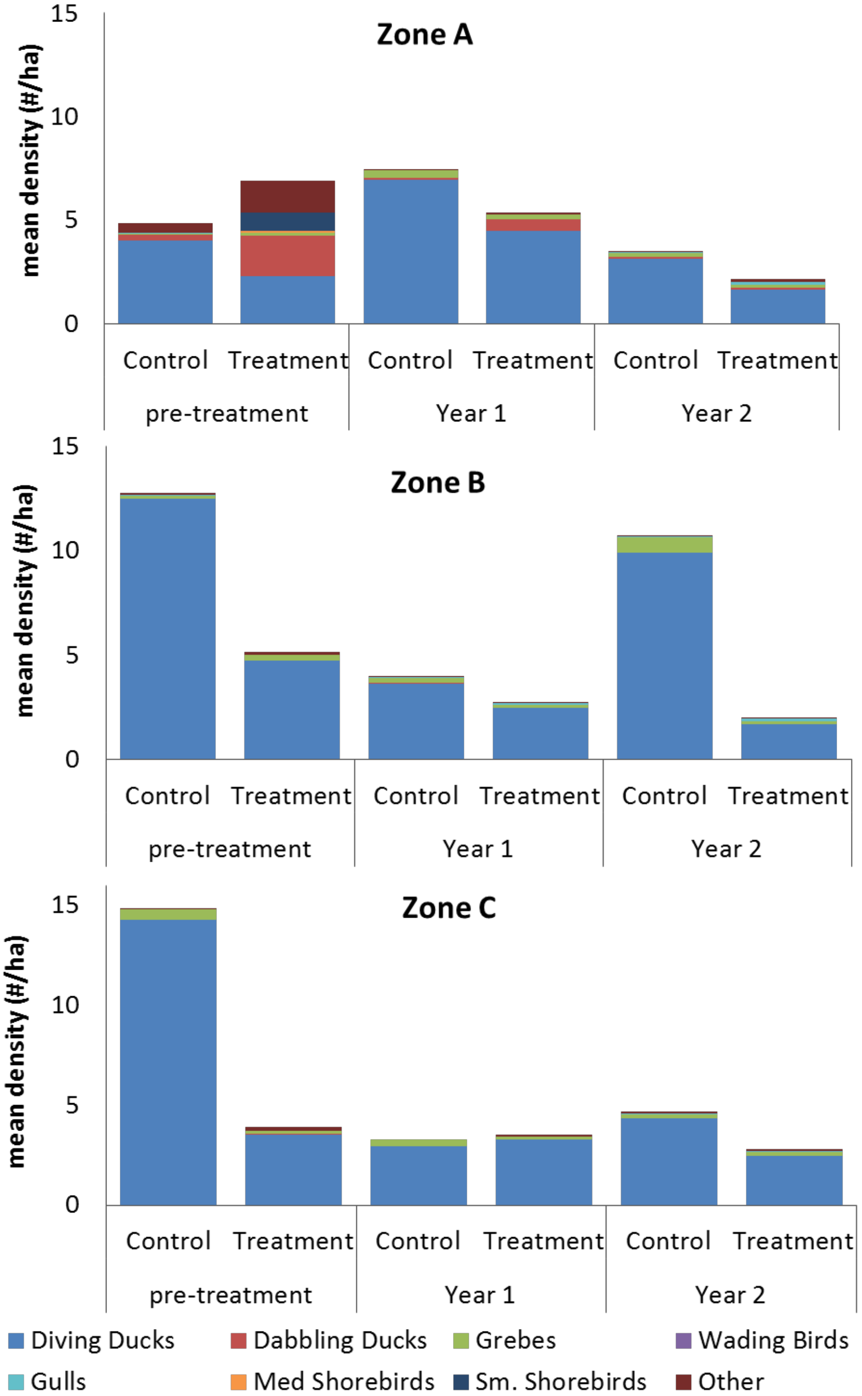

Figure 7. Total mean density of all avian guilds during high tide at The Nature Conservancy (TNC) in treatment and control areas during each of the three years of study. Fall (Sep - Oct) data were excluded, as surveys were not conducted during this period in the pre-treatment year.

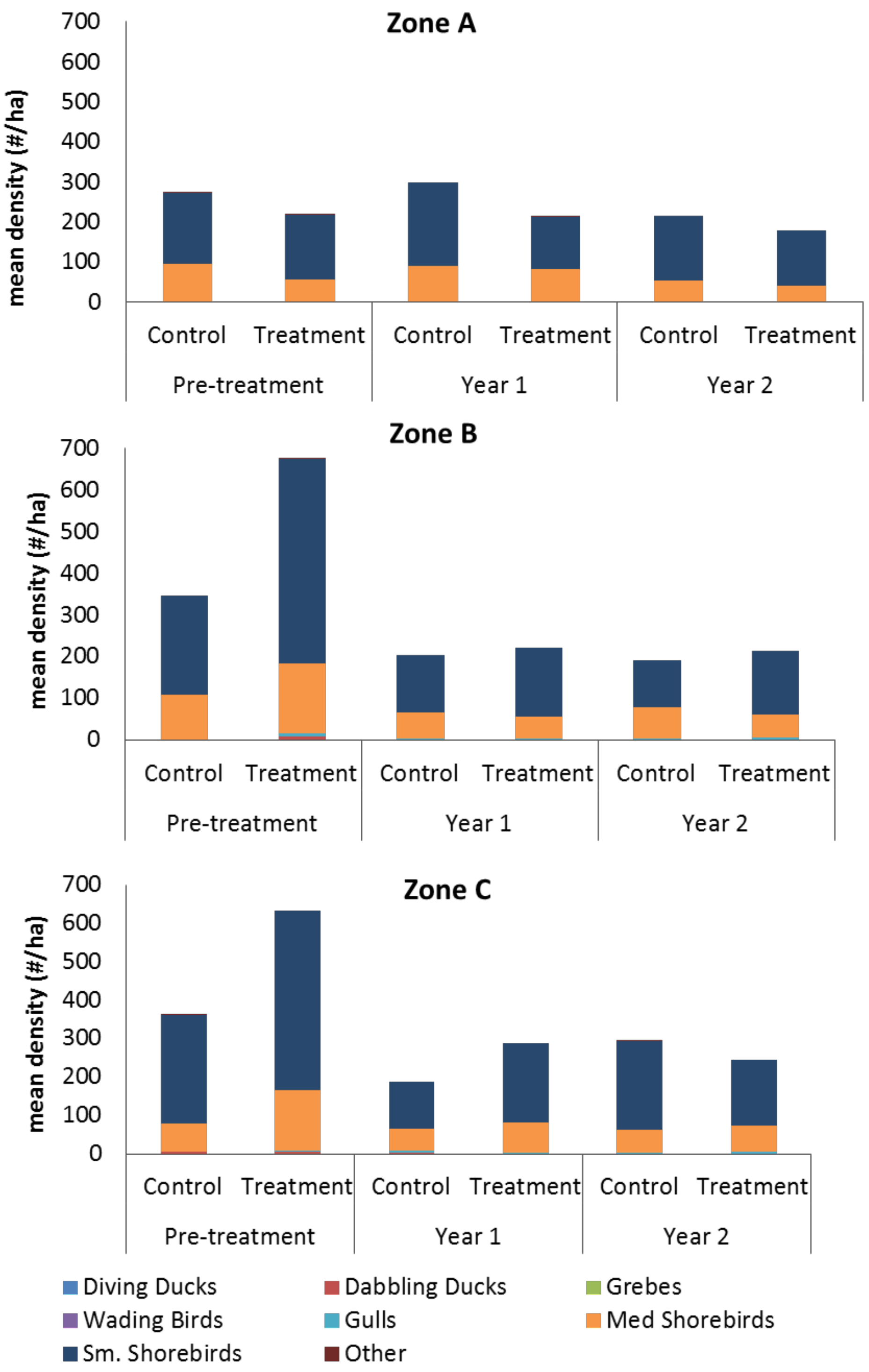

Figure 8. Total mean density of all avian guilds during low tide at ELN in treatment and control areas during each of the three years of study. Mean density was calculated for each zone where the tideline was present. Fall (Sept. and October) data were excluded, as surveys were not conducted during this period in the “pre-treatment” year.

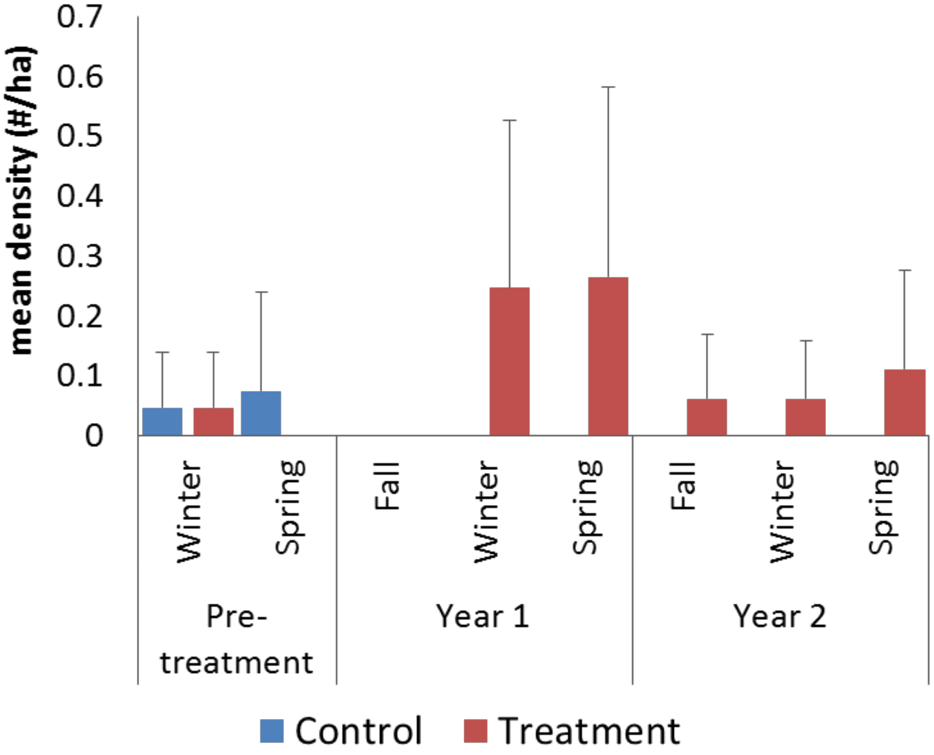

Figure 9. Mean seasonal density of wading birds in zone B of ELN in treatment and control plots at low tide during each year of the study.

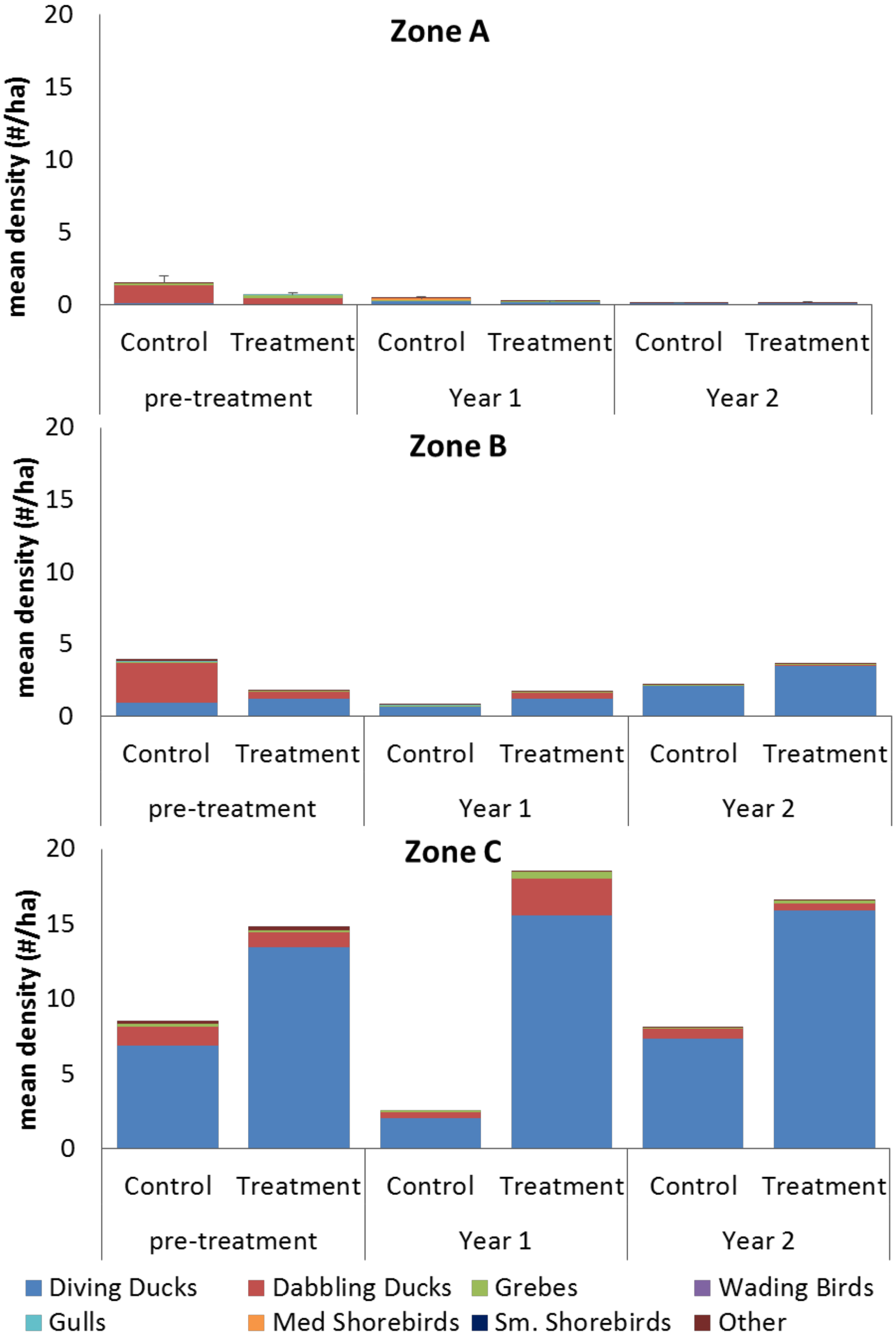

Figure 10. Total mean density of all avian guilds at Eden Landing North during high tide. Fall data were excluded, as surveys were not conducted during this period in the "pre-treatment" year.

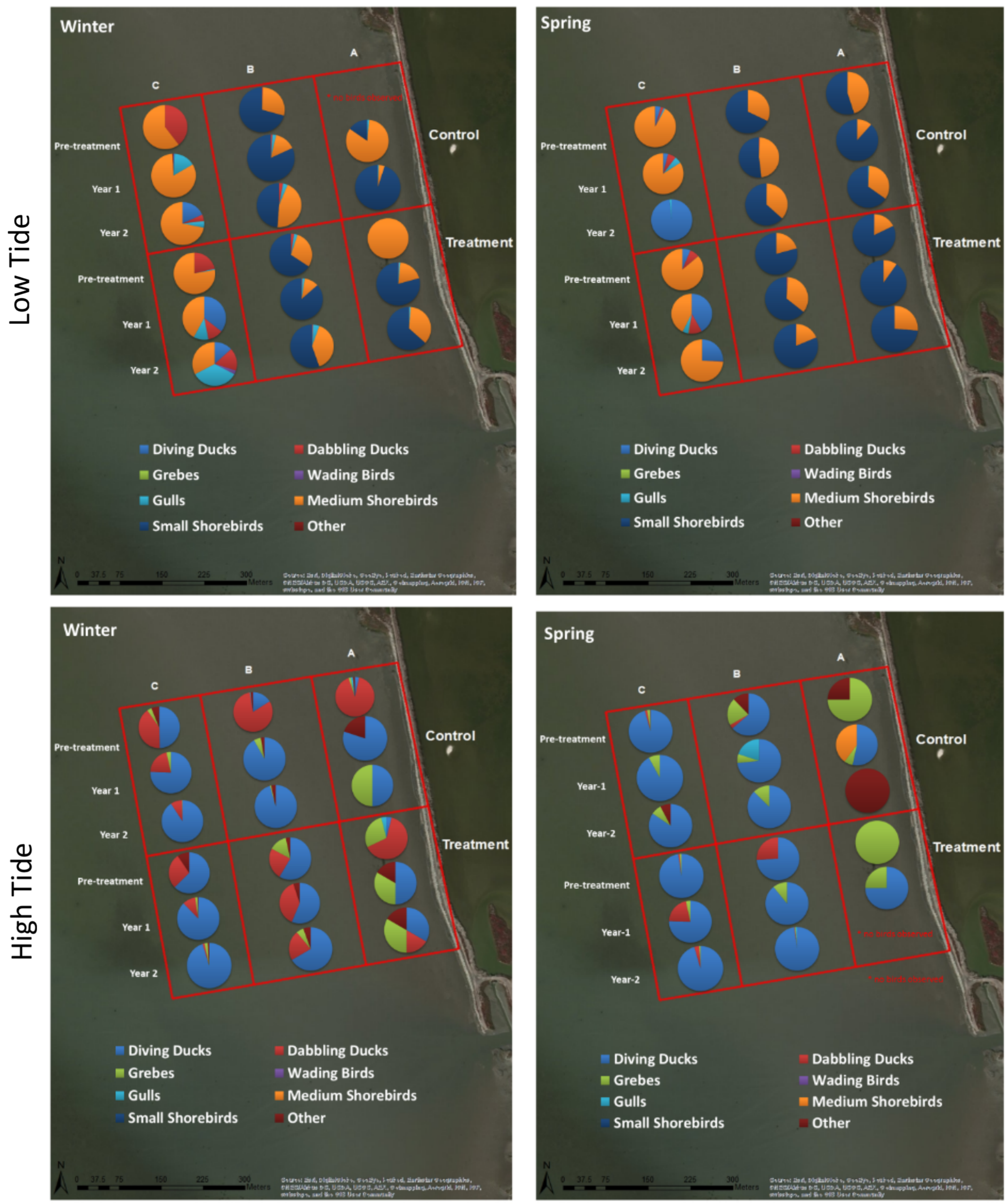

Figure 11. Mean relative density avian guilds in each survey zone (A, B, and C) of treatment (top) and control (bottom) areas during low tide (top panels) and high tide (bottom panels) in winter (left) and spring (right) at ELN. Charts in zones of each area represent pre-treatment (top rows) and treatment year 1 (middle rows) and year 2 (bottom rows).

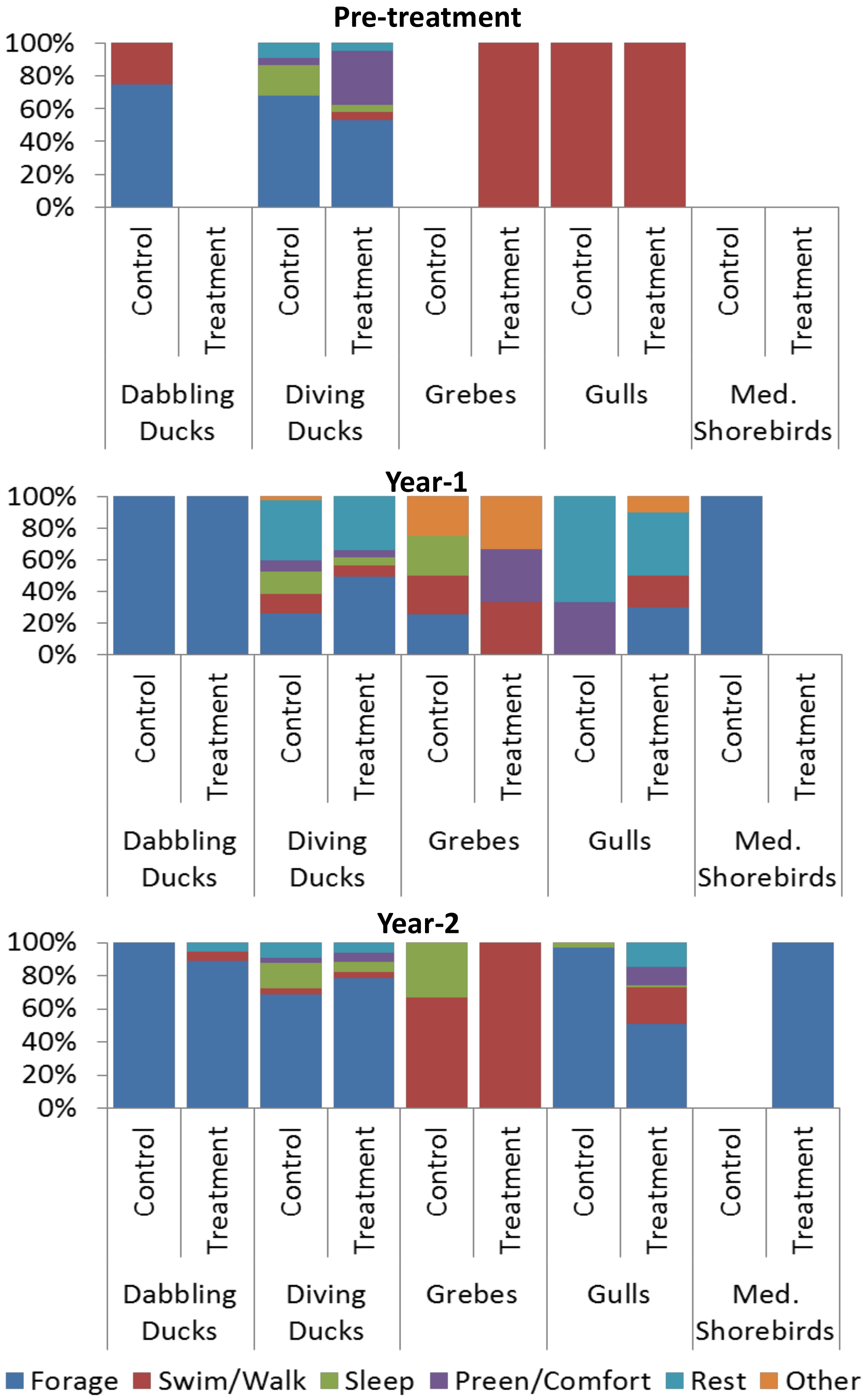

Figure 12. Avian behavior by guild from scan surveys at TNC in zone B of both the treatment and control areas during low tide during pre-treatment (top), year-1 (center) and year-2 (bottom).

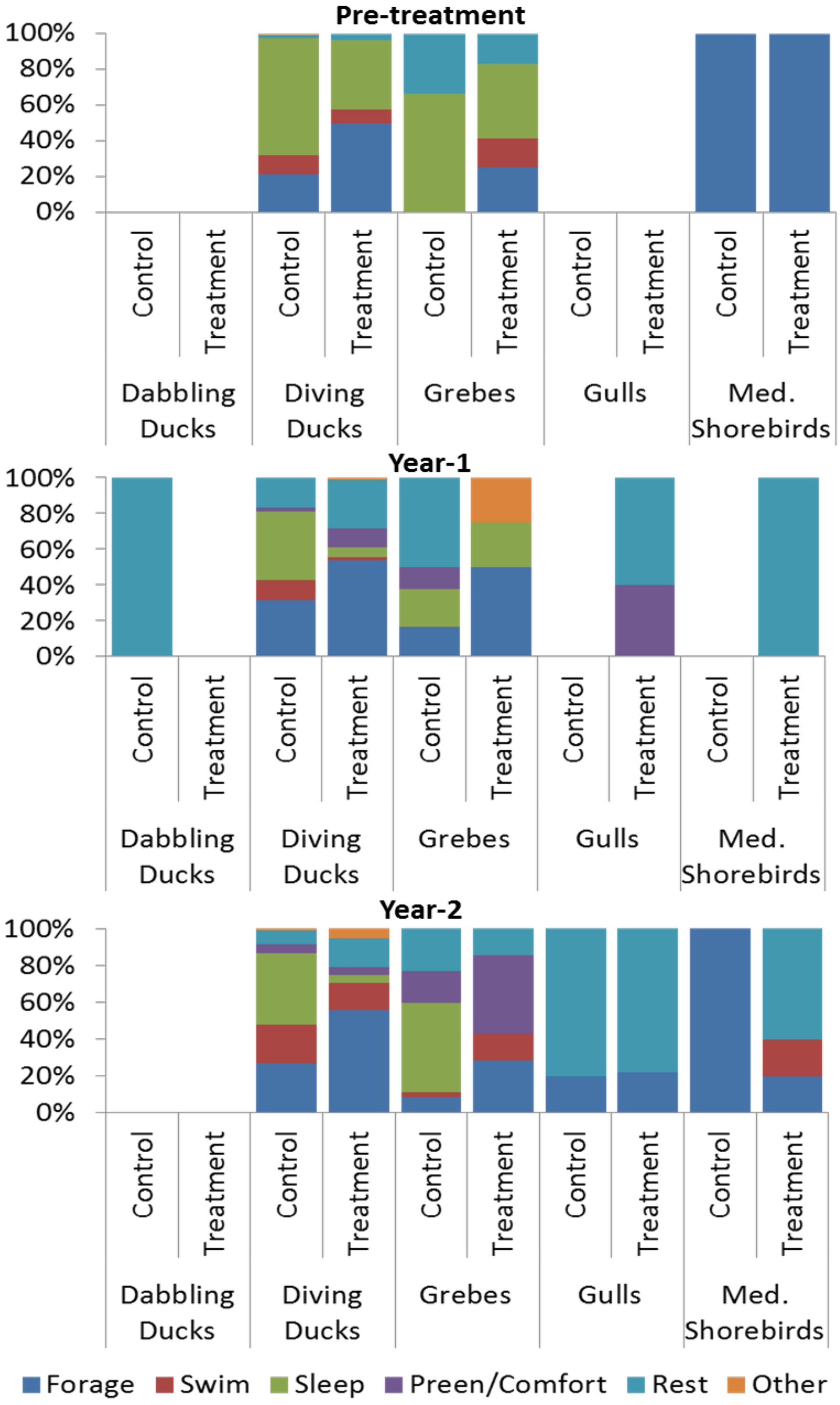

Figure 13. Avian behavior by guild from scan surveys at TNC in zone B of both the treatment and control areas during high tide during pre-treatment (top), year-1 (center) and year-2 (bottom).

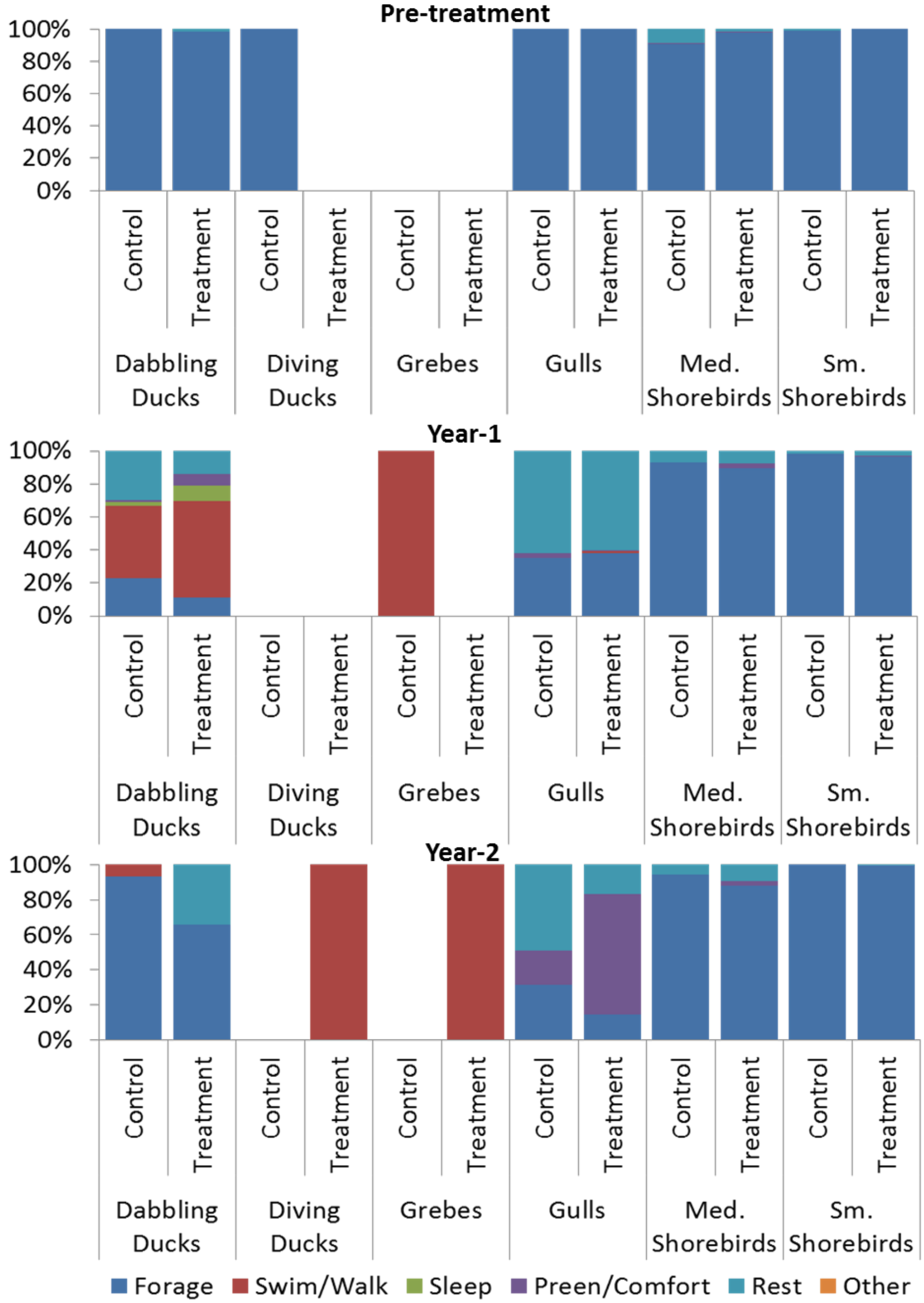

Figure 14. Avian behavior by guild from scan surveys at ELN in zone B of both the treatment and control areas at low tide during pre-treatment (top), year-1 (center), and year-2 (bottom)

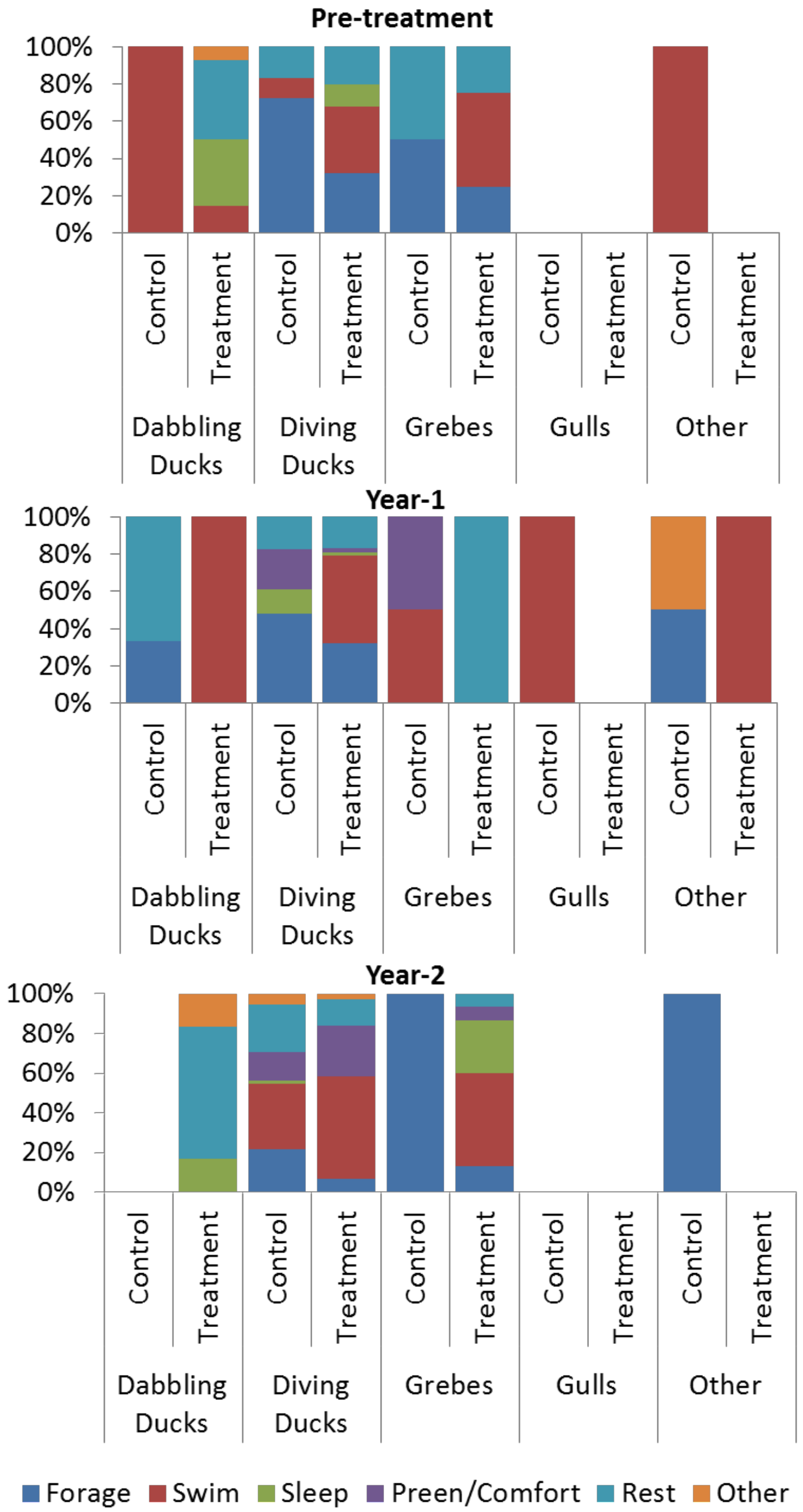

Figure 15. Avian behavior by guild from scan surveys at ELN in zone B of both the treatment and control areas at high tide during pre-treatment (top), year-1 (center), and year-2 (bottom)

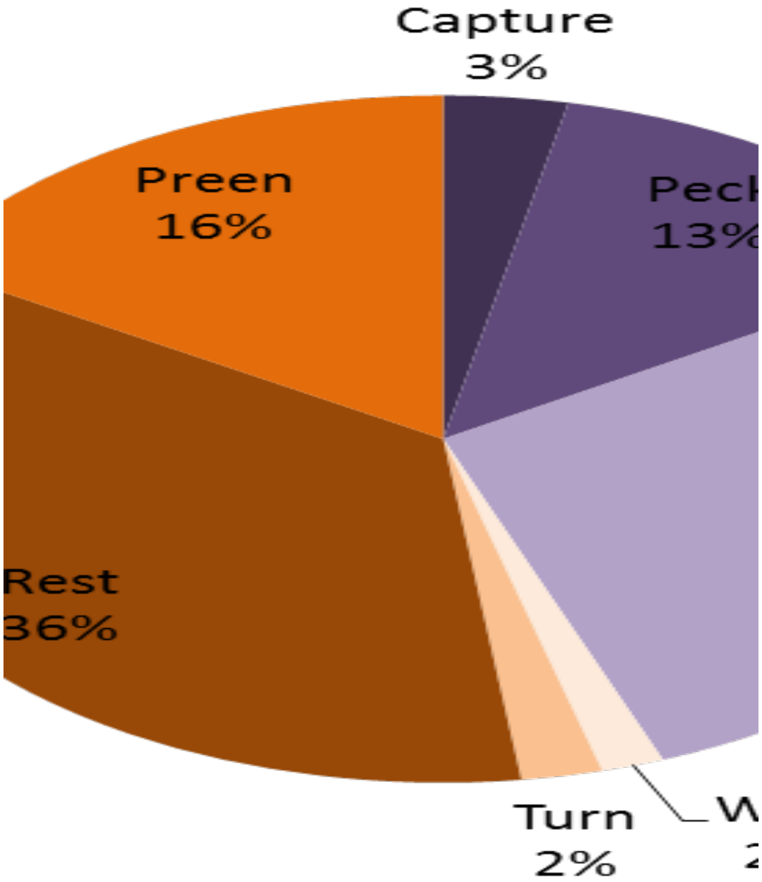

Figure 16. Behavioral data from focal observations of BLOY at TNC at LT in Zone B in year-2 only.

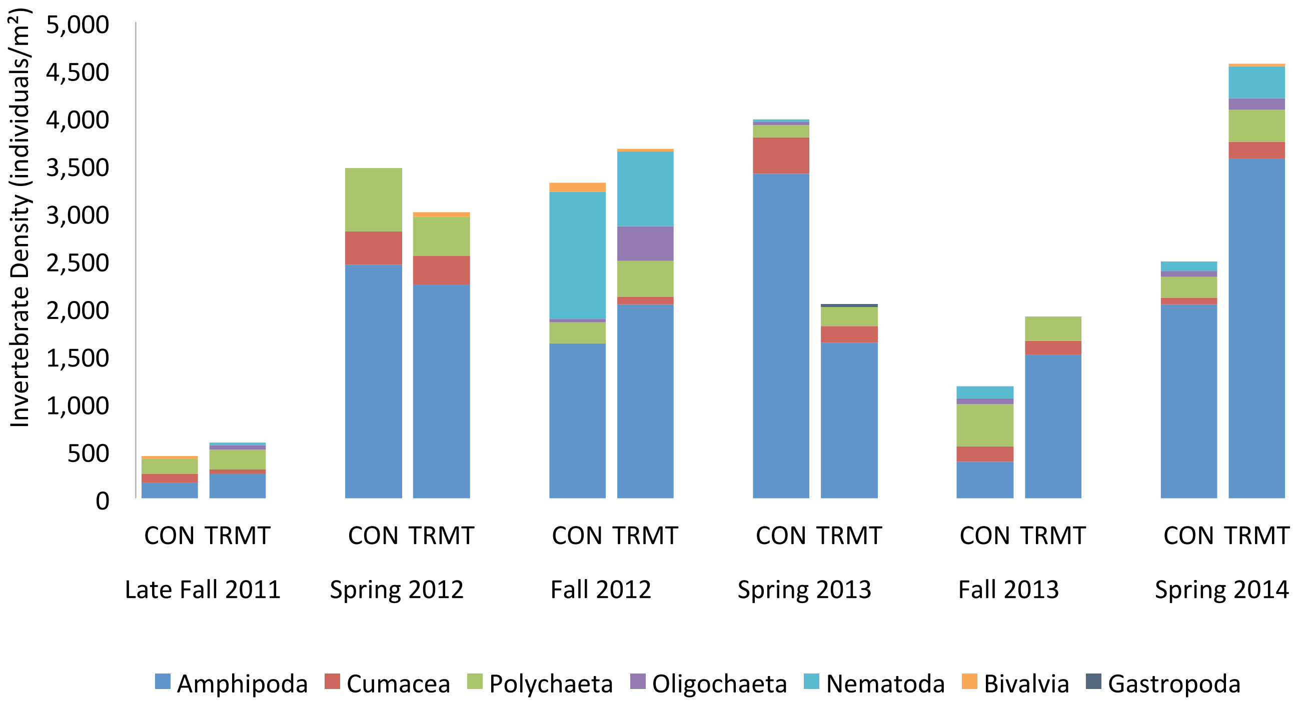

Figure 17. Mean pre- (late fall 2011 and spring 2012) and post-installation (fall 2012 and 2013, spring 2013 and 2014) invertebrate densities (individuals/m²) in zone B cores from treatment (TRMT) and control (CON) areas at TNC.

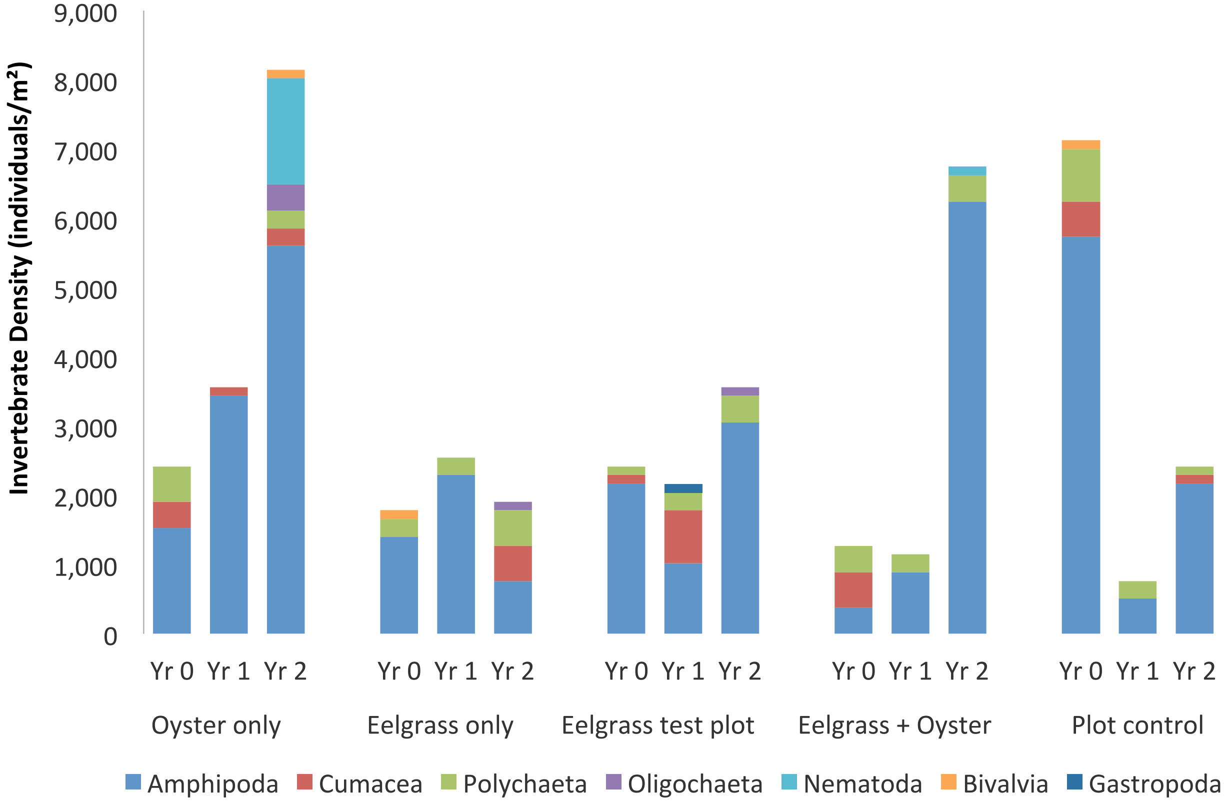

Figure 18. Mean pre- (Yr 0: spring 2012) and post-installation (Yr 1: spring 2013; Yr 2: spring 2014) invertebrate densities in zone B TNC treatment plots.

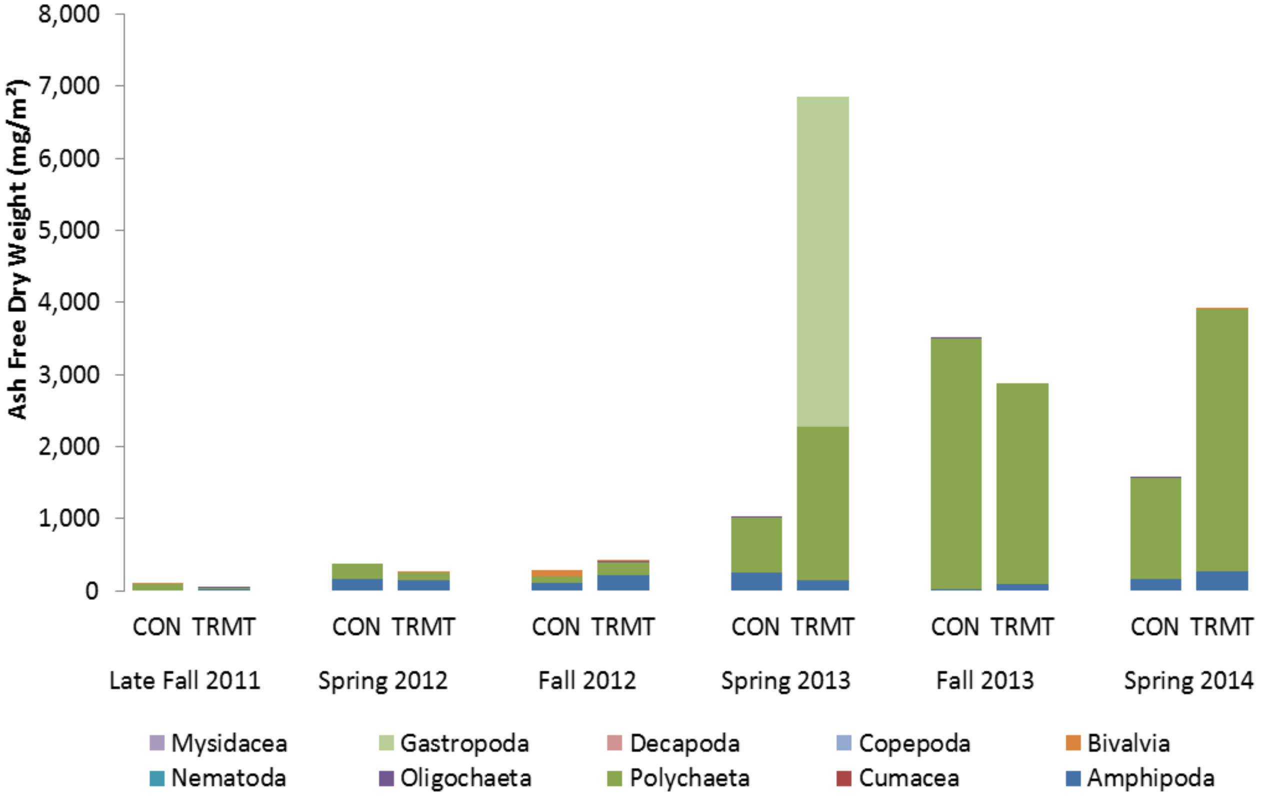

Figure 19. Mean pre (late fall 2011 and spring 2012) and post-installation (fall 2012 and 2013, spring 2013 and 2014) invertebrate ash-free dry weight (mg/m²) in zone B from treatment and control areas at TNC.

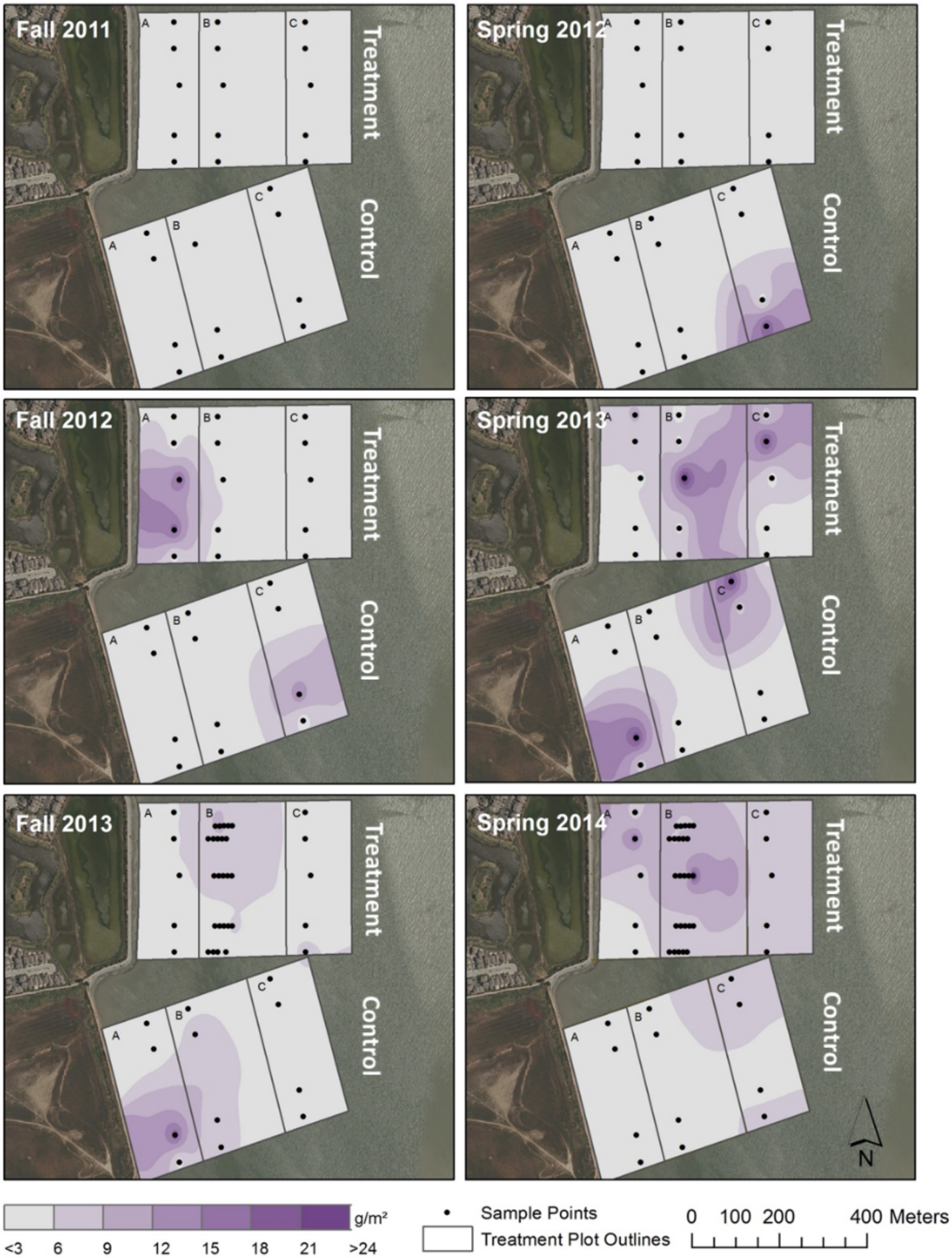

Figure 20. Interpolated maps of invertebrate biomass (AFDM mg m^{-2}) from sediment cores (black circles) in survey zones (A, B, and C) in control and treatment areas at ELN TNC in late fall 2011, spring 2012, fall 2012, spring 2013, fall 2013, and spring 2014.

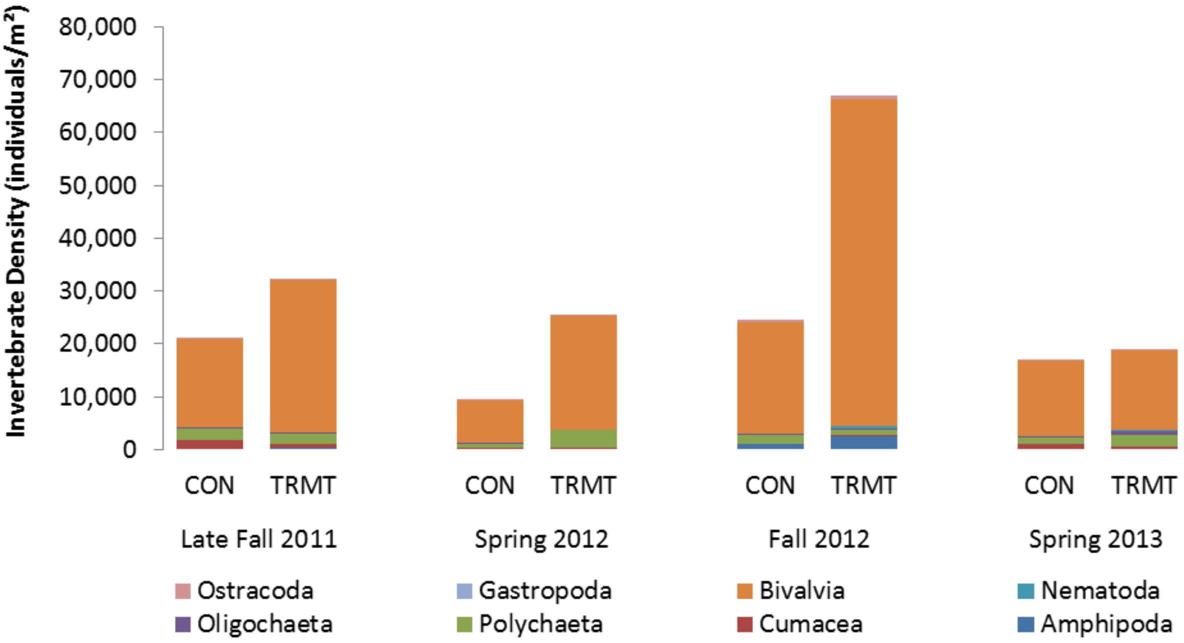

Figure 21. Mean pre (late fall 2011 and spring 2012) and post-installation (fall 2012 and spring 2013) invertebrate densities (individuals/m²) in zone B cores from treatment and control areas at Eden Landing North.

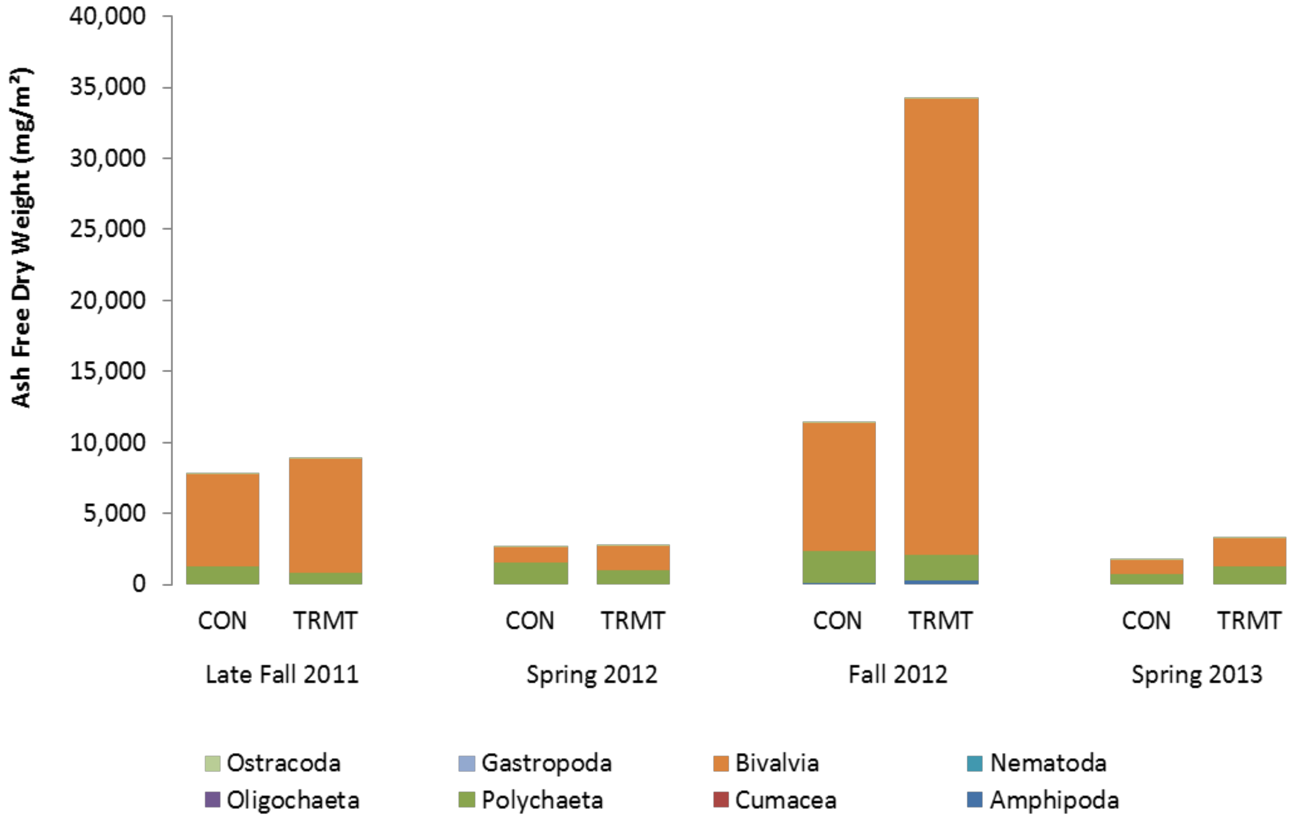

Figure 22. Mean pre (late fall 2011 and spring 2012) and post-installation (fall 2012 and spring 2013) invertebrate ash-free dry weight (mg/m²) in zone B cores from treatment and control areas at Eden Landing North.

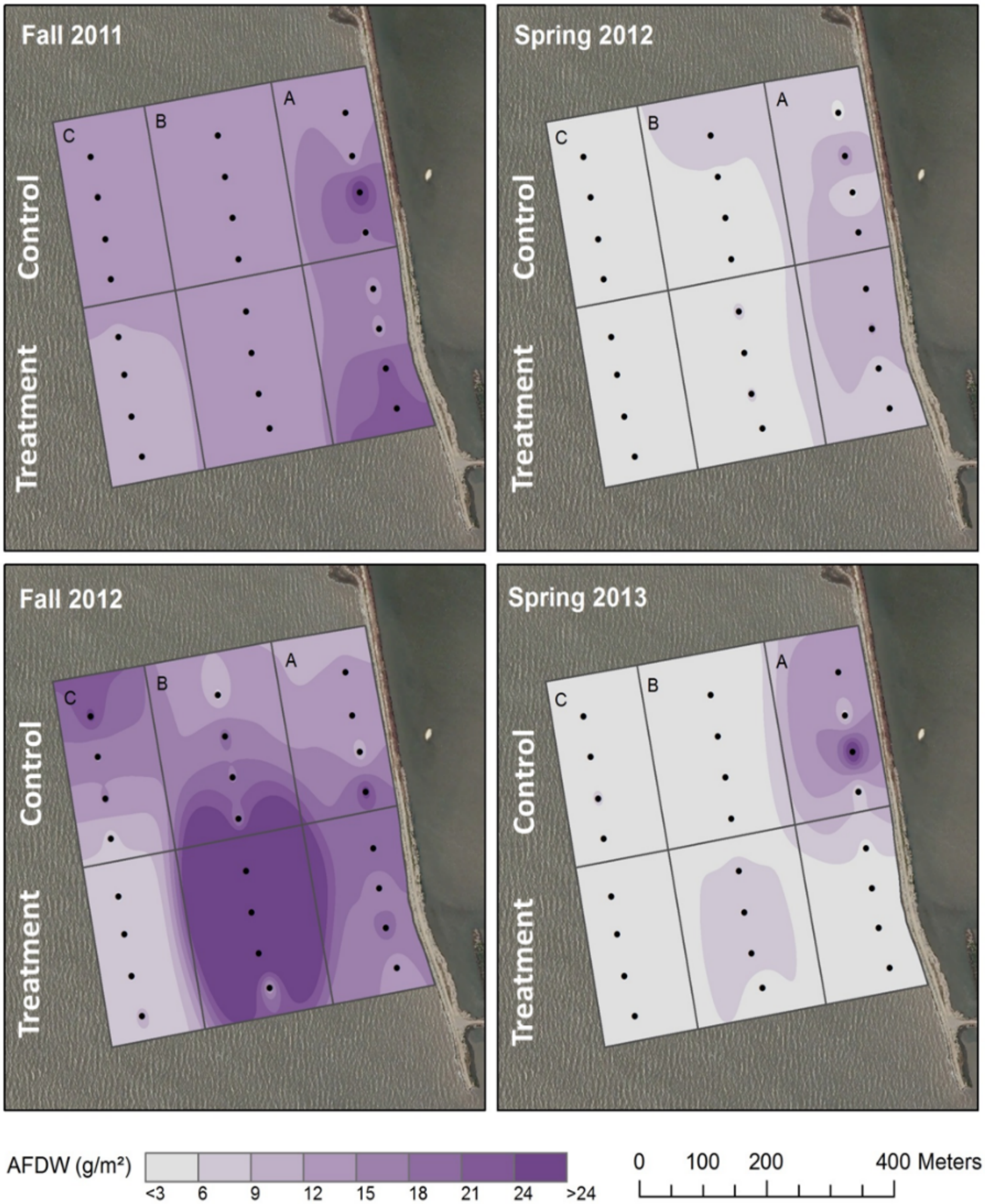

Figure 23. Interpolated maps of invertebrate biomass (AFDM mg m^{-2}) from sediment cores (black circles) in survey zones (A, B, and C) in control and treatment areas at ELN in late fall 2011, spring 2012, fall 2012, and spring 2013.

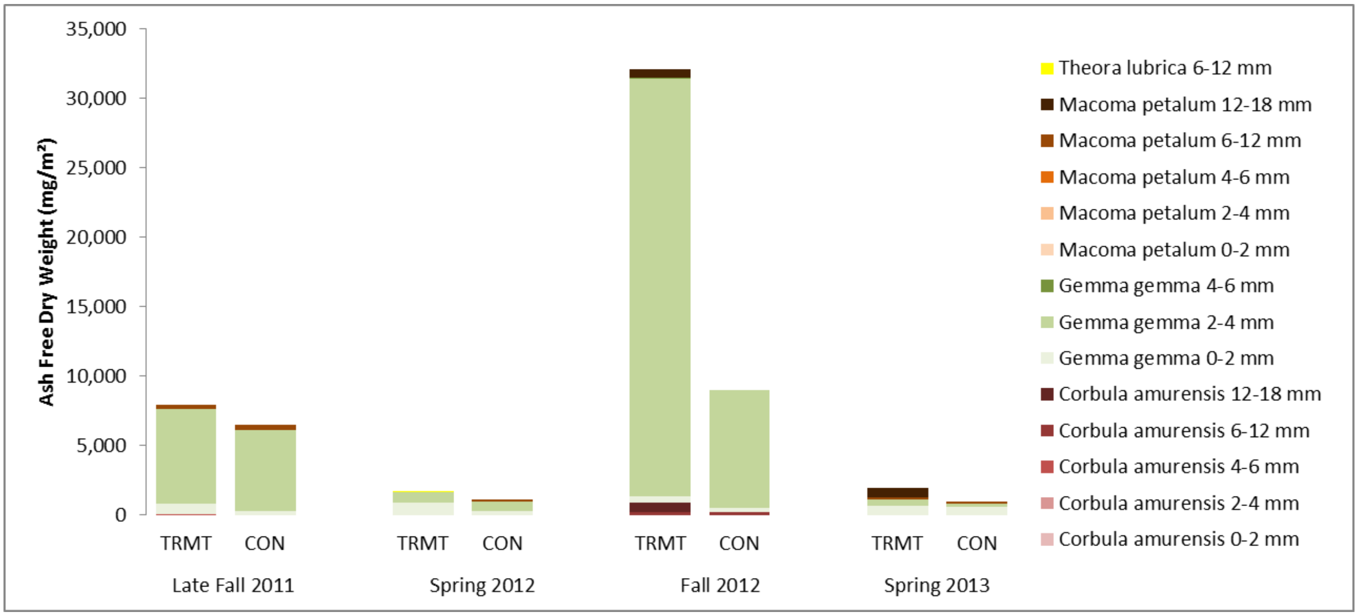

Figure 24. Mean pre (late fall 2011 and spring 2012) and post-installation (fall 2012 and spring 2013) bivalve ash-free dry weight (mg/m²) in zone B cores from treatment and control areas at Eden Landing North.

Table 1. Shannon Diversity Index and species richness of the Nature Conservancy (TNC) and Eden Landing North (ELN) at low (LT) and high tide (HT) in control and treatment areas for all zones in all years. For ELN, diversity was calculated only from zone B when the tide line was in zone B.

	TNC				ELN			
	LT		HT		LT		HT	
Diversity	Control	Treatment	Control	Treatment	Control	Treatment	Control	Treatment
Pre-treatment	2.14	1.68	1.10	1.96	1.47	1.38	1.55	1.07
Year 1	2.29	2.22	1.33	1.70	1.89	1.74	1.37	1.19
Year 2	2.19	2.41	1.33	1.78	1.71	1.31	0.81	0.40
Richness								
Pre-treatment	22	17	15	19	13	14	13	12
Year 1	25	28	14	20	22	26	12	15
Year 2	26	32	15	17	19	25	10	13

Table 2. Benthic invertebrate density between control and treatment areas for all sampling periods at TNC.

	Late Fall 2011		Spring 2012		Fall 2012		Spring 2013		Fall 2013		Spring 2014	
	Control	Treatment	Control	Treatment	Control	Treatment	Control	Treatment	Control	Treatment	Control	Treatment
Amphipoda												
Caprella drepanochir	-	-	127.3	-	-	382.0	-	-	-	-	382.0	127.3
Ampelisca abdita	636.6	1,145.9	5,474.9	7,639.4	6,493.5	8,021.4	10313	3,565.1	1,400.6	3,947.0	4,965.6	3,183.1
Grandidierella japonica	-	-	-	254.6	-	763.9	509.3	636.6	-	127.3	-	891.3
Corophiidae	-	127.3	1,400.6	1,527.9	-	254.6	763.9	1,145.9	127.3	382.0	1,018.6	3,310.4
Monocorophium spp.	-	-	2,801.1	1,782.5	-	763.9	2,037.2	2,801.1	-	3,055.8	1,782.5	10,313.2
Cumacea												
Cumacea	382.0	254.6	1,400.6	1,527.9	-	382.0	1,527.9	891.3	636.6	763.9	254.6	891.3
Nematoda												
Nematoda	-	127.3	-	-	5,347.6	3,947.0	127.3	-	509.3	-	382.0	1,655.2
Polychaeta												
Exogone lourei	-	-	-	-	-	-	-	-	-	-	-	127.3
Glycinde sp.	254.6	-	254.6	254.6	254.6	636.6	254.6	127.3	254.6	254.6	127.3	127.3
Phyllodocidae	-	-	127.3	-	127.3	254.6	-	-	-	-	-	-
Neanthes succinea	-	-	127.3	-	-	-	-	254.6	-	-	-	254.6
Sabaco elongatus	382.0	891.3	1,145.9	1,273.2	509.3	382.0	127.3	509.3	636.6	636.6	254.6	636.6
Capitellidae	-	127.3	-	127.3	-	-	-	-	-	-	-	-
Sabellidae	-	-	-	-	-	-	127.3	-	763.9	254.6	127.3	-
Spionidae	-	-	-	-	-	-	-	-	127.3	-	-	-
Streblospio benedicti	-	-	1,018.6	382.0	-	636.6	-	127.3	-	-	382.0	382.0
Cirratulidae	-	-	-	-	-	-	-	-	-	127.3	-	127.3
Oligochaeta												
Oligochaeta	-	254.6	-	-	127.3	1,782.5	127.3	-	254.6	-	254.6	636.6
Bivalvia												
Corbula amurensis	-	-	-	127.3	-	-	-	-	-	-	-	-
Gemma gemma	127.3	-	-	127.3	127.3	127.3	-	-	-	-	-	-
Theora lubrica	-	-	-	-	254.6	-	-	-	-	-	-	-
Musculista senhousia	-	-	-	-	-	-	-	-	-	-	-	127.3
Gastropoda												
Philine auriformis	-	-	-	-	-	-	-	127.3	-	-	-	-

Table 3. Benthic invertebrate density between control and treatment areas for all sampling periods at Eden Landing North.

	Late Fall 2011		Spring 2012		Fall 2012		Spring 2013	
	Control	Treatment	Control	Treatment	Control	Treatment	Control	Treatment
Amphipoda								
Ampelisca abdita	-	509.3	-	-	1527.9	3819.7	-	127.3
Grandidierella japonica	-	-	-	-	-	1145.9	-	127.3
Corophiidae	127.3	254.6	-	-	636.6	127.3	-	-
Monocorophium spp.	254.6	127.3	-	-	1782.5	5347.6	-	-
Cumacea								
Cumacea	7002.8	3183.1	1145.9	1527.9	509.3	127.3	3692.4	2164.5
Ostracoda								
Myodocopa	254.6	636.6	509.3	1273.2	1782.5	3565.1	382.0	1273.2
Podocopa	-	-	636.6	127.3	-	127.3	-	127.3
Nematoda								
Nematoda	127.3	-	-	127.3	382.0	1145.9	382.0	636.6
Polychaeta								
Eteone lighti	127.3	636.6	-	-	382.0	-	891.3	1018.6
Exogone lourei	-	-	127.3	-	-	-	-	127.3
Glycinde spp.	127.3	-	254.6	1145.9	509.3	891.3	254.6	382.0
Neanthes succinea	636.6	254.6	509.3	382.0	2037.2	1400.6	636.6	636.6
Capitellidae	1018.6	636.6	382.0	1145.9	1273.2	1145.9	636.6	763.9
Streblospio benedicti	6493.5	6748.2	2164.5	10440.6	2291.8	1273.2	2419.2	5856.9
Oligochaeta								
Oligochaeta	509.3	127.3	127.3	127.3	509.3	891.3	1273.2	2928.5
Bivalvia								
Corbula amurensis	127.3	127.3	254.6	763.9	127.3	254.6	127.3	127.3
Gemma gemma	67227.1	115610.2	31703.7	85179.8	84288.5	247008.6	56277.2	59587.6
Macoma petalum	254.6	254.6	127.3	127.3	-	127.3	509.3	382.0
Theora lubrica	-	-	-	127.3	-	-	-	-
Gastropoda								
Gastropoda	-	-	-	-	127.3	-	-	-