DRAFT

The effect of off-road vehicles on barrier beach invertebrates of the temperate Atlantic Coast, U.S.A.

Jacqueline Steinback[1] and Howard Ginsberg[2]

[1] Department of Plants Sciences/Entomology

Woodward Hall

University of Rhode Island

Kingston, RI 02881

[2] USGS Patuxent Wildlife Research Center

Coastal Field Station, Woodward Hall - PLS

University of Rhode Island

Kingston, RI 02881

Abstract

The effects of off-road vehicles (ORVS) on invertebrates inhabiting seaweed debris (wrack) and supratidal sands on energetic beaches in the northeastern United States were studied at Cape Cod National Seashore, MA, and Fire Island, NY. Cores, wrack quadrats, and pitfall traps were used to sample four beaches, which all had vehicle-free sections in close proximity to ORV corridors, allowing for paired traffic/no-traffic samples at these sites. A manipulative experiment was also performed by directly driving over nylon-mesh bags filled with eelgrass (*Zostera marina*) wrack that had been colonized by beach invertebrates, then subjected to treatments of high-, low-, and no-traffic.

Pitfall trap samples had consistently higher overall invertebrate abundances in vehicle-free than in high-traffic zones on all four beaches. In contrast, both wrack quadrats (with intact wrack clumps) and the cores taken directly beneath them did not show consistent differences in overall invertebrate abundances in areas open and closed to vehicles. Overall abundance of wrack was lower on beaches with vehicle traffic. The talitrid amphipod *Talorchestia longicornis* and the lycosid spider *Arctosa littoralis*, both of which roam widely on the beach and burrow in supratidal bare sands as adults, were always less abundant in beach sections open to vehicle traffic, regardless of the sampling method used. Other invertebrates, such as oligochaetes (family Enchytraeidae) and Tethinid flies (*Tethina parvula*), both of which spend most of their lives within/beneath wrack detritus, showed either no response or a positive response to traffic disturbance. In

the drive-over experiment, different species responded differently to traffic. The tenebrionid beetle *Phaleria testacea* (85% larvae) was significantly less abundant in disturbed wrack bags than in controls, while *Tethina parvula* (90% larvae) showed the reverse trend. Therefore, ORVs adversely affected beach invertebrates, both by killing or displacing some species, and by lowering wrack abundance, thus lowering overall abundance of wrack dwellers. However, for some interstitial detritivores vehicle disturbance apparently facilitated mechanical breakdown of wrack and increased observed abundances.

Our results suggest that alternating opening and closing of adjacent beaches to vehicle traffic allows recolonization of wrack clumps in newly-closed beaches from two sources: wrack-dwelling species from intact wrack clumps that remain on the disturbed beach and wide-ranging species from adjacent undisturbed beaches. Research on rapidity of recolonization from these sources is needed to optimize schedules of beach opening and closing for conservation of supratidal invertebrates.

Introduction

Motorized off-road vehicles (ORVs, off-highway vehicles-OHVs, or four-wheelers) are driven on exposed beaches world-wide, yet their use is a subject of persistent concern on government-managed beaches. Unfortunately, published studies on the effects of beach driving on invertebrate populations of energetic beaches are often insufficient for beach managers to make informed decisions on conservation policy. Patchy distributions and high variability in time and space (Colombini & Chelazzi, 2003; Defeo & McLachlan, 2005) have made beach invertebrates prohibitively challenging to quantify and led to conflicting or inconclusive results in the measurement of macroinvertebrate response to any chronic, large-scale anthropogenic disturbances (e.g., Zaremba et al., 1979; Schoeman et al., 2000).

In the U.S., beach driving is often limited to the most exposed, energetic beaches, where wrack debris (organic matter consisting of dislodged macrophytes and marsh plants) collects on the backshore and serves as the main source of ecosystem nutrients (Polis and Hurd, 1996; Colombini and Chelazzi, 2003). These wrack deposits are largely spring-tide and storm-driven driven and occur less frequently and in lower abundance than on protected shores. However, they still attract abundant and species-rich invertebrate populations (e.g., Lavoie, 1985; Inglis, 1989; Polis and Hurd, 1996; Dugan et al., 2003), which play a vital role in temperate barrier beach food chains.

While wrack debris or the wrack-line is well-known in the northeastern United States as foraging habitat for shorebirds (Gibbs, 1986; Hoopes, 1993; Elias et al., 2000), there are only a few invertebrate community studies on these populations (Behbehani & Croker, 1982; Steinback, 1999; Army Corps of Engineers 2005). The effects of ORVs have often been presumed, but not successfully documented for wrack communities. A better understanding of wrack community members on exposed beaches is necessary to help managers set ORV policies that balance recreation with natural resource protection.

Off-road vehicles have been shown to affect beach and dune systems by crushing vegetation and breaking beach grass rhizomes (Broadhead & Godfrey, 1979a; Leatherman & Godfrey, 1979; Rickard et al., 1994), preventing embryonic dune formation (Zaremba et al., 1979), and facilitating sand mobility and habitat loss with sea-level rise (Visco, 1977; Broadhead & Godfrey, 1979a; Anders & Leatherman, 1981, 1987; Brown and McLachlan, 2002). In addition, beach driving has been correlated with decreases in abundance and productivity of state- and federally-protected shorebirds (e.g., piping plovers (*Charadrius melodus*) (Goldin, 1993; Melvin et al., 1994), common (*Sterna hirundo*) and least terns (*Sterna antillarum*) (Blodget, 1979)), nesting sea turtles [e.g., the Loggerhead, *Caretta caretta* (Hosier et al., 1981)]; and the seabeach amaranth (*Amaranthus pumilus*), often forcing closures to popular beaches and vigorous natural resource monitoring.

Many authors have concluded that beach macrofaunal communities can withstand human disturbances (Godfrey, Leatherman, & Buckley, 1978;

Schoeman et. al, 2000; Weslawski et al., 2000a), because they are already well adapted to their unstable substrata. This may be true of intertidal species, such as polychaetes, mollusks, and crabs, which have been resilient in the long-term to 'pulse' (*sensu* Bender et al., 1984) disturbances [such as, nearshore beach nourishment (Gorzelany, 1983; Rakocinski et al, 1996; Burlas et al., 2001), bulldozing/beach scraping (Peterson et al., 2000), and intermittent harvesting (Kyle et al., 1997; Lavery et al., 1999; Schoeman et al., 2000)], because new recruits can quickly recolonize suitable habitat (Nelson, 1985; Brown & McLachlan, 1990). Intertidal species also seem resistant to 'press' or chronic disturbances by both human trampling (Jarmillo et al., 1996; Moffett, 1998) and ORVs (Wolcott & Wolcott, 1984; Van der Merwe & Van der Merwe, 1991), because they are usually burrowed in wet, compact sands at low tide, when driving events are most likely to occur (Wolcott & Wolcott, 1984; Anders & Leatherman, 1987).

In contrast, species living above the daily swash (in supratidal/backbeach areas) appear less adapted to disturbances (Zaremba et al, 1979; Watson et al., 1996, Gomez & Defeo, 1999; Defeo & Gomez, 2005), so that they warrant separate consideration. Oniscid isopods can be crushed when burrowed supratidally (Van der Merwe & Van der Merwe, 1991), and they decline on highly populated beaches (Brown, 2000), along with talitrid amphipods (Weslawski et al.; 2000a & 2000b) in temperate regions and ghost crabs (e.g., *Ocypodid quadrata*) (Steiner & Leatherman, 1981; Gao & Xu, 2002) in milder locations. Ghost crabs are killed by vehicles while foraging (Wolcott and Wolcott, 1984), and they are buried during beach scrapings (Peterson et al., 2000; Brown & McLachlan, 2002), though they apparently can survive being run over in their soft-sand, back-beach burrows (Wolcott and Wolcott, 1984). In addition, ORVs have also been implicated in the historical disappearance of the northeastern beach tiger beetle (*Cicindela dorsalis dorsalis*) from much of its original geographical range (U.S.F.W.S., 1993).

In the last decade, several studies have addressed the effects of disturbance on macroinvertebrates in ephemeral wrack deposits (Dugan et al., 2003, de la Huz et al., 2005). Both oil spill clean-ups (de la Huz et al., 2005) and beach rakings or "cleanings" (Engelhard & Withers, 1998; Dugan et al., 2003), which involved wide-spread removal of wrack deposits, showed immediate reductions in the abundances of semi-terrestrial crustaceans, insects, and their predators (Dugan et al., 2003). In this study, we re-visit two U.S. National Seashores, which served as study sites in the late 1970's for comprehensive government investigations into the effects of ORVs on beach/dune systems (Anders and Leatherman, 1981). Here, we focus on the effects of off-road vehicles on supratidal invertebrates.

First, we compare four different wrack-laden beaches in the northeastern U.S. (three within Cape Cod National Seashore, one within Fire Island National Seashore) that have neighboring sections of ORV-traveled and ORV-free beach (the 'analytical approach,' Buchanan, 1976), and second, we perform a controlled direct-impact study, in which we drive over colonized wrack clumps near Ballston Beach, MA, to assess the effects. By replicating our sampling at four beaches (Schoeman et al., 2000) and using several sampling methods, we strove to maximize the chances that observed differences between treatment (traffic) and control (non-traffic) sites were due to ORV activity. In the manipulative experiment, we controlled the level and timing of the traffic that the wrack-associated species received. In addition, we compared accompanying environmental variables that may be good indicators of the effect of traffic on invertebrate habitat.

Methods

A. Comparative Study

<u>Study sites</u>

In the summers of 2001-2002, comparative samples were taken from exposed beaches within the Cape Cod National Seashore (CACO) (avg. summer temp. 19.5º), a pristine government-protected area along the northeastern edge of Cape Cod. Three study beaches were chosen along the CACO ORV route: 1) Race Point North (RPN)—the usual area for SCVs (such as campers, trailers), 2) Race Point South (RPS)—located .4 miles south of RPN, and 3) Coast Guard (CG) beach, North Truro, which was opened in 1998 to night fishing only. Both Race Point sites are located on the Provincetown barrier spit and have been open to vehicles since the 1960's (Broadhead and Godfrey, 1979a). All sites had a route over the dune that allowed vehicle entrance and travel along the beach in the one direction that is open to vehicles. Fencing and signs prevented drivers from entering the neighboring sides of each beach, which were closed to vehicles but often occupied by sunbathers. Therefore, samples from traffic and non-traffic areas could be taken within a few hours of each other, limiting the temporal and spatial variation among sites.

A fourth access point, located at the Oakleyville vehicle-cut, near Sailor's Haven (SH) on Fire Island National Seashore, was sampled as part of preliminary ORV research in the summer (avg temp. 22º) of 1995. Fire Island is a dynamic barrier island lying just south of Long Island, NY, with vehicle access limited to

245 permitted residents and various personnel (~173), and most driving is restricted to early morning and evening hours during the summer. Both Cape Cod and Fire Island National Seashores have intermediate-type beaches (Wright and Short, 1983) with semidiurnal, astronomical tides and typical seasonal shifts between storm (winter) and recovery (summer) profiles (*sensu* Komar, 1976) (Table 1). All sites can experience exceptionally high tides during hurricanes and Nor'Easters (Bokuniewicz et al, 1993), however Fire Island is more wave-dominated than the Cape Cod beaches (Table 1).

Sampling Areas

On either side of each vehicle cut (between 100-200m wide), traffic (T) and non-traffic (NT) sample areas were designated by 100m-wide stretches of beach (parallel to the water) that were roughly equidistant from the point where vehicles enter the beach (after Anders & Leatherman, 1981, Fig. 47). A benchmark (PVC pipe) with known elevation (height above NGVD88, provided by USGS-Woods Hole, MA) was established 50m into each area, at the toe of the dune/bluff closest to the beach, to serve as reference. At SH, height was measured relative to NGVD83. Initial descriptive data on foredune/bluff characteristics, such as height/slope, vegetation composition and cover, and the presence of vegetation fronts (the seaward edge of dune vegetation, Anders & Leatherman, 1981) were collected at least once during each summer of study within the T/NT areas. Foredunes were considered the dunes closest to the water that usually fronted larger primary dunes of higher elevation. Vegetation factors were considered important, because many invertebrate scavengers and predators inhabit vegetated dunes, and travel from the dunes to the wrack to feed (Brown and McLachlan, 1990).

Transects

Samples were taken twice at Cape Cod sites in 2001 (July 19-Aug. 2 & Aug. 10-23) and 2002 (June 3-8 & Aug. 8-14) and three times at Sailor's Haven (SH) in 1995 (July 29-31, Aug. 10-11 & Aug. 23-24). Within each 100m-wide sample area, five points were randomly selected for dune toe-to-swash transects. The foredune toe was considered the point where steep dune slopes soften and merge onto the back beach. Changes in profile slope were measured at roughly 1-m intervals, using a hand-held digital level (SmartTool™, Macklanburg-Duncan, Oklahoma City, OK, USA) run along a tape measure from the dune to swash at low tide. Profiles were used to measure bare beach widths and intertidal slopes/zones for each transect, from which averages could be calculated. Profiles from transects of the first sampling period were averaged together and plotted to display representative contours of each beach area. These measurements were taken, because beach morphology can affect alongshore abundances of spp. and amount of wrack deposition (Defeo & McLachlan, 2005).

To quantify the overall amount of wrack within each sampling area, any wrack debris along a profile that intersected the tape (and up to roughly 0.5 meter to either side) was recorded for dimensions (l*w*d), % species composition, and an ordinal rating of wrack consistency (1-5)—or the uniformity of cover.

Therefore, the frequency of wrack/meter on driven and vehicle-free beaches could be compared and the mean density/meter ((l*w*d)/meter^2 of beach) could be estimated. Since the clump was measured at its largest length and width, and was therefore an overestimate of clump cover, an elliptical surface area, estimated using the standard formula (length/2*width/2*PI), was considered more accurate for analysis. These surface area estimates (m^2 wrack/meter of beach) for each transect could then be used to generate an overall % cover for each area (after Dugan et al., 2003).

Invertebrate sampling

Invertebrate sampling focused around wrack deposits, because preliminary samples at the SH site showed that supratidal/backbeach macrofauna congregated there. The wrack was also the area of greatest concern for new dune growth and foraging species (Zaremba et al., 1979). Along each profile, a 0.1m^2 quadrat frame was placed over a random wrack clump to delineate a sample. Clumps were randomly chosen from within driving areas first. If there was no wrack within a driving corridor, then samples were taken (e.g., fresh and old) in the surrounding sample area in proportion to the occurrence of each debris type present. Attempts were also made to sample wrack with quadrat cover over 50%, to minimize any bias associated with different sized wrack samples.

Three sampling methods were then used in each transect, in this order: 1) debris samples, where the wrack within the quadrat frame was measured for environmental variables, cut away, and collected in Ziploc™ bags for later sorting of invertebrates; 2) core samples, in which a beveled PVC pipe (15.24 cm diameter*20 cm depth) cored sand below the sampled wrack, which was then sieved through a 1-mm mesh screen, and bagged for later sorting of burrowed fauna, and finally 3) pitfall trap samples: a 16 oz. (0.5 liter) plastic Solo® cup partially filled with soapy water was set (either in the core hole or within few meters landward of it) for 24 hours, to catch mobile, nocturnal animals, many of which invade wrack from the dunes (Brown and McLachlan, 1990). At Fire Island, more samples could be taken, as only one site was sampled. In 2002, pitfall trap sampling was repeated at CACO sites.

Environmental variables measured within wrack samples included: quadrat percent cover, relative wrack age (categorized qualitatively as fresh, decaying, or old) and % composition (predominantly *Zostera marina* or eelgrass; brown alga--*Ascophyllum nodosum* and *Fucus* spp.; cordgrass or *Spartina alterniflora*; and beach grass, *Ammophila breviligulata*), temperature and humidity at the wrack/sand interface (with a Tri-Sense® meter & RH/Temp probe with sintered bronze filter tip, Cole-Parmer Instrument Co., Vernon Hills, IL, USA), and sand temperature at 10cm depth (w/soil thermometer) beneath wrack. Wrack wet/dry weight, % moisture (water loss upon drying at 60ºC until weights stabilized for 24 hrs), and volume (cubic centimeters) were determined in the laboratory for CACO samples. Core, wrack, and pitfall trap samples were sorted, and invertebrates were identified to lowest possible taxonomic level. SH samples differed in that the wrack debris was sorted for invertebrates in the field (see Steinback, 1999), and wrack frequency on the beach, % moisture, dry weight, volume, and temp./RH under wrack were not measured.

Analysis

For SH, Fire Island, samples consisted of 10 wrack samples and 10-11 pitfall traps taken in three time periods (30 wrack samples/32 pitfall traps in the T and NT areas). CACO sites samples consisted of 10 wrack samples/10 pitfall traps taken from the six areas (3 Traffic/3 Non-traffic) over two time periods in 2001, and two more in 2002 (12 pitfall traps/area). Therefore, while 2-way ANOVAs (treatment ***x*** sampling period) could be used at the Fire Island site, 3-way ANOVAs (treatment ***x*** site ***x*** period) were used at CACO. ANOVAS were performed using SPSS 13.0, 2004 (SPSS, Inc). When desired, the T-method for multiple unplanned comparisons among means (Sokal and Rohlf, 1995) was then used to determine which sites were significant by treatment. A Levene's Test (1960) or an F-max test was used to confirm homogeneity of variances, and data with many zeros or outliers were log (x+1) transformed. If data were not normal, then two-way nonparametric ANOVAs (traffic*period) using the Scheirer-Ray-Hare extension of the Kruskal-Wallis Test were run with BIOMstat, version 3.301 (Applied Biostatistics Software, Inc., Pt. Jefferson, NY, USA). This test was chosen, because it is robust against departures from normality. When traffic*site interactions occurred, then two-way ANOVAs were run at each site individually.

Consistent significant differences in overall abundances or abundances of certain species between T/NT areas at all four beaches were considered probable indicators of ORV disturbance. The same procedures were used on environmental variables, as vehicle effects can be visible through changes in soil microhabitat (Buchanan, 1976; Zaremba et al., 1979). Analysis was performed on both wrack samples and pitfall traps, to assess the effectiveness of each sampling method in trapping different types of organisms (e.g., hoppers, fliers, crawlers, burrowers, wrack affiliated species, back beach species) and in monitoring traffic disturbances.

B. Manipulative Study

The manipulative experiment was performed from late June-mid July, 2002, on a remote, undisturbed beach near Ballston, Cape Cod, 1/10 mile north of the Welfleet/Truro line (Table 1). Freshly deposited eelgrass *Zostera marina* was frozen for 48 hours to kill existing invertebrates, soaked overnight in filtered seawater to simulate being washed ashore, and partitioned (150 gm/clumps) into 81 wide-mesh sacs (20” Nylon replacement nets, Pepper Net Co., Inc., Williamson, NY, USA) that could easily be colonized by all invertebrates <2 inches in diameter.

On the morning after the June 25th full-moon, the bags were placed above the spring high tide line on a 50m stretch of beach partitioned into 9 sections, 9 bags per section, and tethered in place using fishing line and stakes. Bags were arranged into 2 rows (2 m long and 2 m apart) per section, perpendicular to the shore, and subjected to one of three treatments (1) high traffic, bags run over 10 times/sampling day; 2) low traffic, bags run over 2 times/sampling day; 3) control, bags not run over. A Chevrolet Suburban (curb weight 4634 lbs.) with tires (245/75-16) lowered to 12-15 psi and driven at speeds of @ 10 miles/hour, consistent with Park regulations, was used to apply treatments. This speed also ensured all treatment bags within a section were run over simultaneously.

Sampling occurred over a three-week period, with samples collected on days 1, 2, 4, 7, 10, 13, 16, 19, & 22. During sampling, one bag was removed from each of the nine beach sections (3 replicates of each treatment), placed carefully into double Ziploc™ bags—along with some handfuls of the underlying sand, and left over night in a Berlese funnel to extract colonizing invertebrates. Relative humidity and temperature were measured at the wrack/sand interface, as well as wrack bag dimensions (l*w*d), level of bag burial, and temperature at 10cm below the wrack. Invertebrates were hand-picked out of the samples, identified, and stored in 75% ethanol. Average invertebrate abundances and abundant species were analyzed using 2-way ANOVAs (treatment ***x*** period).

Results

Comparative Analysis

Traffic level

In 2001, traffic-level was highest at the Race Point-North (RPN) site (267+/-19 cars/day), followed by Race Point–South (RPS: 187+/-12), and Coast Guard (CG) in N. Truro (Figure 1). Traffic level was lowest at Fire Island, but the level was estimated from transect counts of vehicle tracks. Driving at both Cape Cod and Fire Island sites is mostly limited to the back-beach, 10-20 feet from the foot of the dune (to avoid injury to beach grass rhizomes) and 10-feet landward of the berm crest (for safety reasons). However, there were some differences among the sites as to exactly where vehicles drove. Within RPN and CG traffic areas, traveling vehicles were mainly restricted to driving corridors (~7m and ~5m wide) about 8-10m from the narrow, sparse vegetation fronts, extending from the primary dune at these two sites. At RPN, campers and self-contained vehicles (SCVs) parked along the berm top, and so the berm crest limited the width of the ORV corridor (Figure 2). At CG, the ORV corridor was mainly limited by tides (Figure 3). At RPS, there was no consistent ORV lane, and vehicles could drive along a wide range of the back beach (est. track width at 21+/-1), starting ~18m from the dune vegetation (Figure 4). Finally, at Sailor's Haven, the track width was not measured, but visible tracks (on average) ran diagonally over the storm wrack that collected at low points between summer and winter berms, about 26m from the profile stake (Figure 5).

Vegetation surveys

The vegetation surveys showed no consistent differences in dune vegetation between traffic and non-traffic areas. Of the three CACO sites, only Race Point North-T and NT areas supported both densely vegetated foredunes and dense vegetation fronts (~15 m wide) (Figure 2), consisting mainly of American beach grass (*A. breviligulata*) (~92%), beach pea (*Lathyrus maritima*) (~5%), and dusty miller (*Artemisia stelleriana*) (~3%). Due to storm erosion, the foredunes of Race Point-South T and NT areas were only sparsely vegetated with exposed beach grass roots, but sea rocket (*Cakile edentula*) and sandwort (*A. peploides)* were growing 5m from the base of the dune (Figure 4). At Coast Guard beach, steep eroding bluffs that were poorly vegetated (1% T and 3% NT) with beach grass and dead beach grass/roots backed both T and NT areas (Figure 3). However, the NT area had a densely vegetated foredune (composed of *A. breviligulata*, *L. maritima, and A. stelleriana*), while the T area had just a few sparse beach grass plants. Though the dune profiles at Sailor's Haven were not measured, both T and NT areas had low foredunes (~1-2m high), sporting wide, dense beach grass fronts that grew seaward during the summer (Figure 5). SH-T's vegetation front was not as dense as on the NT side (personal observation). Therefore, of the four sites, only the Coast Guard site had marked differences between traffic and non-traffic site in back-beach vegetation.

General Profiles

There were no measured differences between traffic and non-traffic beaches that held for all four sample sites, and overall profile shapes in T and NT areas were similar (Figures 2-5). However, all sites except Coast Guard did have traffic areas with higher overall beach elevations than non-traffic areas during sampling. In addition, at all sites except Race Point North, slopes in non-traffic areas were steeper than within traffic areas (ANOVA: overall treatment effect at Cape Cod: F=18.8 df=1, 24 P<0.0002). The Race Point North-traffic beach had a wider supratidal bare beach (~37T vs. ~32NT), due to a narrower vegetation front than the non-traffic area, but intertidal zone widths (averaging 27-28m) and slopes (1:8) did not differ (Figure 2). The RPS site had the widest beaches (77+/-2 NT, 78+/-2 T) and bare back-beaches (~50m wide), with intertidal zones ~29 m wide for both T and NT areas. RPS slopes averaged 1:8.6 in the non-traffic and 1:8.9 in traffic areas (Figure 4).

Coast Guard-T and NT area profile shapes differed the most of the 4 sample sites. The NT area had more defined beach berms than the T area, with a significantly steeper intertidal slope (ave. slopes.1:6.3 to 1:8:3, F=19.2 df=1,8 p<0.002) and a wider overall beach (53+/-2 NT vs. 49+/-1 T, F=5.3 df=1,16 p=0.04) in both periods (Figure 3). However, the non-vegetated back beach width (where driving could occur or would occur if the site was open to traffic) was roughly equal on both sides (~31.5m T vs. 30m NT). Finally, at the Sailor's Haven site, the non-traffic area had more pronounced berms and consistently steeper intertidal slopes (ave. for 3 periods: 1:6.3 NT vs. 1:7.5 T), though not significantly so. Average beach (55+/-3 NT, 58+/-1 T), intertidal zone (21+/-3 NT, 21+/-1 T), and back-beach widths (~26m) were not significantly different between SH traffic and non-traffic samples (Figure 5). Therefore, Coast Guard was the only site with large differences in beach morphology and vegetation fronts between traffic- and non-traffic areas during the time of sampling.

Environmental variables

Abundance and distribution of wrack differed on beaches with and without traffic. Wrack was significantly less frequent in traffic than non-traffic areas, both on the beach as a whole (freq/m^2, $F= 73.4$ $df=2, 48$ $P<0.001$) and within ORV corridors (Scheirer-Ray-Hare tests by site: CG: $F=6.7$ $df=1,16$ $P=0.02$; RPS: $F=22.6$ $df=1,16$ $P<0.002$; and at RPN: $F=5.2$ $df=1,16$ $P=0.04$) (Figure 6). Rankings of wrack consistency per clump (i.e. whether the thickness was consistent throughout the sample) and wrack cover (within sample quadrats) were also higher in non-traffic areas, but estimates of average density and surface area per wrack clump did not differ between NT and T samples. Since the overall number of clumps was lower in the traffic areas, the overall percent cover of wrack per sampling area (calculated as total wrack surface area (m^2)/100 m-long sampling area of beach (m^2)) was also significantly lower on beaches with traffic (Table 2).

Beach invertebrate abundances

Abundances of beach invertebrates in wrack/core samples did not differ consistently within traffic and non-traffic areas at either Fire Island or Cape Cod sites (Figure 7). In contrast, abundances in pitfall trap samples were consistently lower in traffic areas than in non-traffic areas at both Fire Island (Figure 8a) and Cape Cod (Figures 8b & c). At Cape Cod, the average number of species per sample also varied within pitfall traps (9.6+/-0.5 NT, 7.1+/-0.5 T; ANOVA: treatment effect, F=13.1 df=1,60 P=0.001), but not within wrack/core samples (Wrack/core: 6.7 +/-0.7 NT, 5.4 +/-0.7 T; ANOVA: treatment effect, F=1.9 df=1,48 P=0.17). Dominant taxa, listed in order of abundance (Table 3), included oligochaetes, tethinid flies, talitrid amphipods, and beach-inhabiting coleoptera. Some species were consistently more abundant in areas without traffic. For example, the beach hopper *Talorchestia longicornis* (Figures 9 & 10) and the wolf spider *Arctosa littoralis* (Figures 11 & 12) were less common in traffic areas when sampled using either wrack/core or pitfall trap methods. However, other species showed no consistent difference in traffic and non-traffic areas, such as the tethinid *Tethina parvula* and enchytraeid oligochaetes (Figures 13 & 14, Table 2).

Experiment results

Average abundances were 8.1 (± 1.0 SE) in the control bags, 6.1 (± 0.7) in the low-traffic bags, and 5.5 (± 0.7) in the high-traffic bags (Figure 15a), but these treatment differences were not significant at the 0.05 level (ANOVA: treatment effect, F=2.7, df=2,72, P=0.07). The lack of significance among treatments may have resulted from an emergence of tethinid fly larvae solely within high-traffic bags during period three (ANOVA: treatment, $F=5.6$, $df=2,24$, $P=0.01$). Larvae of the tenebrionid beetle *Phaleria testacea*, the most abundant species in all three treatments (31% of all individuals), were significantly lower in the bags subjected to traffic (ANOVA: treatment, $F=4.8$, $df=2,72$, $P=0.01$) (Figure 15b). Other abundant species included various microlepidoptera (not common wrack dwellers) and an unknown species of collembola (Entomobryidae). The only environmental variables showing a significant difference between treatments were bag volume and % of wrack clumps buried (Table 4).

Discussion

Abundances of beach macroinvertebrates captured in pitfall traps were consistently lower on sandy beaches subjected to off-road vehicle traffic in this study (Figure 8). Although invertebrate abundances in intact wrack clumps did not differ between traffic and non-traffic beaches at our sites, our direct impact experiment shows that traffic can lower wrack invertebrate abundances as well, and in incremental amounts with traffic level (Figure 15). Since both wrack frequency and percent cover were consistently lower on beaches open to off-road vehicles (Figure 6), driven beaches could be expected to have lower overall abundances of wrack invertebrates in addition to the lower abundances actually seen in pitfall trap samples.

Abundances of common species in traffic samples were consistently lower than in non-traffic areas at all four sample sites, over several years, and using both manipulative and natural experiments. Therefore, our results indicate that ORV traffic lowered the abundances of beach invertebrates on these beaches. The species most strongly affected were amphipods (e.g., *Talorchestia longicornis*) and predators (e.g., the wolf spider *Arctosa littoralis*) that roam widely on the beach, and could have been affected by vehicle traffic in either a density-mediated (e.g., mortality by crushing) or trait-mediated (e.g., avoidance of vehicles) manner. Certain species clearly reacted to off-road vehicles more than others (in both the manipulative and natural experiments), and, therefore, a multi-faceted approach might be needed in studying ORV impacts on beach invertebrates.

Many recent studies have clearly established that wrack removal lowers the diversity and abundance of beach invertebrates—in both wrack and on open sand—at disturbed sites (e.g., De la Huz et al., 2005; Dugan et al., 2003; Yaninek, 1980). Our study further demonstrates the importance of wrack beach invertebrate habitat (with highest abundances caught in wrack debris samples, Table 4), even on high-energy beaches with sparse, ephemeral deposits. Therefore, our study findings also imply that frequency or cover of wrack might be used as an indicator of ORV traffic.

Our results suggest several possible mechanisms for the effects of off-road traffic on invertebrate populations. One mechanism for the lower invertebrate abundances in traffic areas is that traffic lowers the overall amount of wrack on these beaches by destroying, scattering or burying it. Zaremba et al, 1979, found that wrack clumps run over by vehicles were more scattered, shredded, or dispersed than control clumps. In our high-traffic areas, this would ultimately result in less wrack available for both surface colonization and sampling. Dry scattered remains of wrack were often seen in our traffic areas, especially at Race Point North, which received the highest level of traffic in a condensed area. We also found that wrack that was run-over was more likely to be compressed into deep tire ruts and buried by wind-blown sand (Table 4).

There are also several possible reasons why certain species were more affected by ORVs than others. For instance, in the wrack/core samples, which did not show differences between traffic and non-traffic areas, the two most common taxa were tethinid fly larvae/pupae and enchytraeid oligochaetes (comprising 37%

of wrack/core abundances combined). Both of these taxa are detritivores, which were highly localized to the moist, fresh wrack at our sites. The abundance of these taxa in high-traffic areas could have resulted from the destruction of older wrack by vehicles on high-traffic beaches, leaving only the freshest wrack more available for sampling. Higher moisture content recordings were found in the wrack samples taken from high-traffic (Table 2), indicating that the high-traffic samples were more favorable habitat for these taxa. It is also possible that rather than being fresher, intact clumps, the wrack sampled in the traffic area might have been temporarily moistened by vehicle impact, because it was compressed in vehicle ruts. Anders and Leatherman (1987) found that sand in vehicle ruts could actually be temporarily moistened, as interstitial water was forced to the surface by compaction. However, under continued disturbance, this wrack would be dried out much faster than undisturbed wrack, as moistened sand is mixed with surface sand and exposed to summer temperatures (Zaremba et al., 1979).

In the traffic experiment, in which naturally colonized wrack bags were directly run over, the same two taxa, tethinid fly larvae and enchytraeid oligochaetes, again showed a preference for wrack subjected to traffic treatments. For the tethinid fly larvae, traffic effect was significant, with larvae limited exclusively to wrack bags receiving the highest level of traffic. Oligochaetes were present in extremely low numbers, but showed the same trend. The fact that these two taxa were higher in bags that were definitely run-over further supports the hypothesis that traffic alters the wrack in some way that provided more suitable habitat for these species, at least in the short-term.

Detritivores have been shown to prefer detritus that is broken into smaller pieces, moister, and/or buried (Edwards & Heath, 1963??). Since Zaremba et al., 1979, found that vehicle impact does break up organic material, temporarily increasing the surface area and moisture for colonization and decomposition by bacteria, the high-traffic areas in this study may have had wrack that was both more available and more nutritious for detritivores (e.g., Tenore et al., 1982). Since moisture was not measured in the direct impact study, we cannot be certain that moisture was higher in the traffic bags in this experiment, as it was in the comparative study. Nonetheless, run over wrack bags in the traffic experiment did have a higher burial rate than controls, perhaps helping the treatment bags to maintain more moisture than control bags exposed to summer sun. Despite the preference of these taxa for the high-traffic bags, overall abundances and the most dominant species in the colonized wrack bags, the tenebrionid beetle *Phaleria testacea* larvae, were still highest in the control treatments (Figure 15). *Phaleria* larvae were also associated with higher elevations (i.e., control wrack which was usually not buried) and drier wrack, probably due to a greater risk of drowning than adults. Thus, despite the rise in a few detritivores in traffic bags, our direct impact study indicates that ORV traffic will lower wrack overall invertebrate densities in addition to the observed pitfall trap invertebrate densities.

Species that responded negatively to traffic were caught more effectively by pitfall trap samples in the comparative study. Two common pitfall trap species that were less abundant in high-traffic areas were the beach hopper *Talorchestia longicornis* and the wolf spider *Arctosa littoralis* (comprising 38.5% of total pitfall trap abundances). These species, like many others caught in our pitfall traps, were highly mobile invertebrates that wander the beach at night, but that burrow in the back-beach or under decaying wrack diurnally. Our observations were that the talitrid *T. longicornis* spent daylight hours burrowed at (juveniles) or above (adults) the last high-tide line, but left burrows at night to feed on fresh, moist wrack deposits of eelgrass *Z. marina* in the intertidal zone (personal observation). On our study beaches, these back-beach areas received the most vehicle traffic by park regulation. Therefore, vehicles could have directly crushed these soft-bodied arthropods.

Some investigators have reported nocturnally active crustaceans run over while foraging in the intertidal (e.g., ocypodids—Wolcott and Wolcott 1984) or killed in their back-beach burrows (e.g., supralittoral isopods at 20 cm depth—Van der Merwe & Van der Merwe, 2001). Other investigators have found lower abundances of talitrids in areas of human activity (Weslawski et al., 2000) and vehicle traffic (Wheeler, 1979). Two alternative possibilities are that these species might have simply avoided the areas disturbed by vehicles or that the physical location of the corridors impeded their nightly migrations.

Pitfall traps were more effective than the wrack/core samples at catching both juvenile and adult *T. longicornis* beach hoppers—at ratios of 5:1 and 40:1 respectively—and the wolf spider *A. littoralis*—at a ratio of 4:1. Because these species are promising indicator species for the effects of off-road vehicles, it is worth discussing their life histories in more detail. The adults of both of these species spend most of the day in moist, supratidal burrows on temperate back-beaches, either in bare sand or under decaying or older wrack. Very small juveniles and immatures, with thinner exoskeletons and higher surface to volume ratios, usually seek shelter closer to or underneath the most recent high-tide wrack, due to their higher risk of desiccation (van Senus & McLachlan, 1985). Wrack cover probably provides substrate stability as well, so that juveniles are not washed out with the tides (Marsden, 1991a).

T. longicornis juveniles can be active diurnally as well, moving about the water's edge at high tide, presumably displaced by rising tides. Adults of *T. longiconis* hop all over the beach nocturnally to feed on fresh, soft or yeast-laden wrack. This behavior of feeding on fresh wrack as it washes in has been observed in other *Talorchestia spp.* (Griffiths & Stenton-Dozey, 1981). During the day, adult *Talorchestia* were buried mostly in bare sand, anywhere from 4-20 cm deep, and inland of the wrack (Smallwood, 1903). *A. littoralis*, as one of these amphipod's main predators, can burrow up to 25 cm deep, and also uses a wide range of beach to hunt at night. Both species were easily caught during these migrations in pitfall traps left 1 m landward of wrack deposits for 24 hours. Therefore, pitfall traps are probably the most effective and simplest sampling method for monitoring ORV effects on beaches using similar species.

Previous studies of the effects of beach traffic on erosion and fore front vegetation have shown that traffic can effectively lower dune elevation, alter profile shape, and impair growth of back-beach vegetation. Though such effects were not observed consistently at all four treatment sites, some traffic sites did show expected signs of ORV impacts on beach profiles. Nevertheless, since profile differences were not consistent between high- and low- traffic areas, they can not explain the consistent differences in invertebrate fauna observed at the four samples sites.

From a management standpoint, we found that the current levels of vehicle disturbance lower beach invertebrate numbers, but that the practice of alternating on/off use of beaches is potentially sufficient to sustain sandy beach invertebrates within the national seashores. In this study, the effect of vehicle traffic differed depending on whether the invertebrate species were primarily wrack-inhabitants or were frequently found on open-sand habitats. Wrack inhabitants were equally abundant within intact wrack clumps on beaches both open and closed to off-road vehicles. Therefore, on beaches that are intermittently closed to traffic, new wrack clumps brought in by the tides can be colonized by wrack species inhabiting older, undisturbed wrack clumps already on these beaches. However, open-beach species, such as *Talorchestia longicornis* and *Arctosa littoralis,* whose adults burrow in the back-beach and brood their young, were directly impacted by beach traffic, and therefore source populations from undisturbed beaches are important for recolonization. For this reason, proximity of undisturbed beaches to high-traffic beaches is apparently important to sustain populations of these species. In conclusion, in order to set effective guidelines for the timing of beach openings and closures, it is important to understand the rapidity of recolonization from these two sources (undisturbed local wrack clumps and nearby undisturbed beaches). Additional studies suggest that the lunar cycle within the active season sets the timing of recolonization of fresh wrack clumps on undisturbed beaches (Steinback, unpublished). Studies of recolonization of both wrack-dwelling and bare-beach species on disturbed beaches after cessation of ORV traffic would be valuable in setting guidelines for the timing of beach closures.

References:

Anders, F. J. and Leatherman, S. P. 1981 Final Report on the effects of off-road vehicles on beach and dune systems, Fire Island National Seashore. University of Massachusetts-National Park Service Cooperative Research Unit, Report **50**, 176 pp.

Anders, F. J. and Leatherman, S. P. 1987 Disturbance of beach sediment by off-road vehicles. *Environmental Geological Water Science* **9**(3), 183-189.

Army Corps of Engineers. 2005.

Behbehani, M.I. and R.A. Croker. 1982. Ecology of beach wrack in northern New England with special reference to *Orchestia platensis*. Estuarine, Coastal and Shelf Science 15:611-620.

Bender, B. A., Case, T. J. and Gilpin, M. E. 1984 Perturbation experiments in community ecology: theory and practice. *Ecology* **65**, 1-13.

Blodget, B. G. 1979 *The effect of off-road vehicles on least terns and other shorebirds.* University of Massachusetts-National Park Service Cooperative Research Unit, Report **26**, 79 pp.

Bokuniewicz, H., A. McElroy, C. Schlenk, and J. Tansky (editors). 1993. Estuarine resources of the Fire Island National Seashore and vicinity. New York Sea Grant Institute. 79^+ pp.

Brazeiro, A. and Defeo, O. 1996 Macroinfauna zonation in microtidal sandy beaches: is it possible to identify patterns in such variable environments? *Estuarine, Coastal and Shelf Science* **42**, 523-536.

Broadhead, J. M. and Godfrey, P. J. 1979a The effects of off-road vehicles on *coastal dune vegetation in the Province Lands, Cape Cod National Seashore.* University of Massachusetts-National Park Service Cooperative Research Unit, Report **32**. 212 pp.

Broadhead, J. M. and Godfrey, P. J. 1979b *The effects of off-road vehicles on* plants of a northern marsh, final report 1974-77. University of Massachusetts-National Park Service Cooperative Research Unit, Report **33**, 79 pp.

Brown, A. C. 2000 Is the sandy-beach oniscid isopod *Tylos granulatus* an endangered species? *South African Journal of Science* **96**, 466.

Brown, A. C.and McLachlan, A. 1990 *Ecology of sandy shores*. Amsterdam: Elsevier, 328 pp.

Brown, A. C. and McLachlan, A. 2002 Sandy shore ecosystems and the threats facing them: some predictions for the year 2025. *Environmental Conservation* **29** (1), 62-77.

Buchanan, K. 1976 Some effects of trampling on the flora and invertebrate fauna of sand dunes. *Discussion Papers in Conservation*, No. **13**. University College London, 42pp.

Burger, J. 1991 Foraging behavior and the effect of human disturbance on the piping plover (*Charadrius melodus*). *Journal of Coastal Research* **7**, 39-52.

Burlas, M., Ray, G. L. and Clarke, D. 2001 *The New York District's Biological Monitoring Program for the Atlantic Coast of New Jersey, Asbury Park to Mana Section Beach Erosion control Project. Final Report*. U. S. Army Engineer District, New York and U.S. Army Engineer Research and

Development Center, Waterways Experiment Station.
Carlson, L. H. and Godfrey, P. J. 1989 Human impact management in a coastal recreation and natural area. *Biological Conservation* **49**, 141-156.
Code of Federal Regulations (CFR), title 36, chapter 1, part 7, sections 7.20 and 7.65.
Colombini, I. and Chelazzi, L. 2003 Influence of marine allochthonous input on sandy beach communities *Oceanography and Marine Biology* **41**, 115-159
De la Huz, R., Lastra, M., Junoy, J., Castellanos, C., and Vieitez, J. M. 2005 Biological impacts of oil pollution and cleaning in the intertidal zone of exposed sandy beaches: Preliminary study of the "Prestige" oil spill. *Estuarine, Coastal and Shelf Science* **65**, 19-29.
Defeo, O. and Gomez, J. 2005 Morphodynamics and habitat safety in sandy beaches: life-history adaptations in supralittoral amphipod. *Marine Ecology Progress Series* **293**, 143-153.
Defeo, O. and McLachlan, A. 2005 Patterns, processes and regulatory mechanisms in sandy beach macrofauna: a multi-scale analysis (Feature Article: Review). *Marine Ecology Progress Series* **295**, 1-20.
Dugan, J. E., Hubbard, D. M., McCrary, M. D. and Pierson, M. O. 2003 The response of macrofauna communities and shorebirds to macrophyte wrack subsidies on exposed sandy beaches of southern California. *Estuarine, Coastal, and Shelf Science* **58S**, 25-40.
Edwards and Heath, 1963 C.A. Edwards and G.W. Heath, The role of soil animals in breakdown of leaf material. In: J. Doeksen and J. Van der Drift, Editors, Soil Organisms, North Holland Publ. Co., Amsterdam (1963), pp. 76–87.
Egglishaw, H. J. 1960 The Life-History of *Fucellia maritima* (Haliday) (Diptera, Muscidae).*The Entomologist* **93**, 225-231.
Elias, S. P., Fraser, J. D. and Buckley, P. A. 2000 Piping plover brood foraging ecology on New York Barrier Islands. *Journal of Wildlife Management* **64**(2), 346-354.
Engelhard, T. and Withers, K. 1998 Biological effects of mechanical beach raking in the upper intertidal zone on Padre Island National Seashore, Texas. Center for Coastal Studies. Texas A&M University-Corpus Christi.
Federal Register (FR), vol 65, p. 70674.
The Federal Register Cape Cod National Seashore; Off-Road Vehicle Use **63** (36), February 24, 1998, 9143-9149.
Frank, J. H., Carlysle, T. C. and Rey, J. R. 1986 Biogeography of the seashore Staphylinidae *Cafius bistriatus* and *C. rufifrons* (Insecta: Coleoptera). *Florida Scientist* **49** (3), 148-161.
Gao, X. and Xu, J. 2002 Impact of Rizhao coastal area exploitation on intertidal habitats and zoobenthic communities. *Studia Marina Sinica* **44**, 61-65.
Gibbs, J. P. 1986 Foraging activities of piping plovers on a sand beach in Maine. Unpublished report submitted to The Nature Conservancy, Maine, 20 pp.
Godfrey, P. J. and Godfrey, M. M. 1980 Ecological effects of off-road vehicles on Cape Cod. *Oceanus* **23**(4), 57-67.
Godfrey, P. J., Leatherman, S. P. and Buckley, P. A. 1978 Impacts of off-road vehicles on coastal ecosystems. **In:** *Coastal Zone '78; Proceedings of*

the Symposium on Technological, Environmental, Socioeconomic & Regulatory Aspects of Coastal Zone Planning and Management, San Francisco, California, March 14-16, pp. 581-600.

Goldin, M. R. 1993. Effects of human disturbance and off-road vehicles on Piping Plover reproductive success and behavior at Breezy Point, Gateway National Recreation Area, New York. Master's Thesis, University of Massachusetts, Amherst. 121 pp.

Gomez, J. and Defeo, O. 1999 Life history of the sandhopper *Pseudorchestoidea brasiliensis* (Amphipoda) in sandy beaches with contrasting morphodynamics. *Marine Ecology Progress Series* **182**, 209-220.

Gorzelany, J. F. 1983. *The effects of beach nourishment on the nearshore benthic macrofauna of Indialantic and Melbourne Beach, Florida*. Master's Thesis, Florida Institute of Technology, Melbourne, Florida. 114 pp.

Hammar-Klose, E. S., Pendleton, E. A., Thieler, E. R.and Williams, S. J. *Relative Coastal Vulnerability Assessment of Cape Cod National Seashore (CACO) to Sea-Level Rise*. USGS Open-File Report **02-223**.

Hoopes, E. M. 1993 *Relationships between human recreation and piping plover foraging ecology and chick survival*. M. S. Thesis, University of Massachusetts, Amherst. 106 pp.

Hosier, P. E., Kochhar, M. and Thayer, V. 1981 Off-road vehicle and pedestrian track effects on the sea-approach of hatchling loggerhead turtles. *Environmental Conservation* **8**(2), 158-161.

Hyatt, J. D. 1972 Behaviour of the wrack dipterans *Fucellia rufitibia* (Anthomyiidae), *Coelopa vanduzeei* (Coelopidae), and *Leptocera johnsoni* (Sphaeroceridae) on a California beach. final Papers Biology **175H**. Hopkins Marine Station of Stanford University. 26 pp.

Inglis, G. 1989 The colonization and degradation of stranded *Macrocystis pyrifera* (L.) C. Ag. by the macrofauna of a New Zealand sandy beach. *Journal of Experimental Marine Biology and Ecology* **125**, 203-217.

Jaramillo, E., Contreras, H. and Quijon, P. 1996 Macroinfauna and human disturbance in a sandy beach of south-central Chile **69**, 655-663.

Jedrzejczak, M. F. 2002 Stranded *Zostera marina* L. vs wrack fauna community interactions on a Baltic sandy beach (Hel, Poland): a short-term pilot study. Part I. Driftline effects of fragmented detritivory, leaching and decay rates. *Oceanologia* **44**(2), 273-286.

Jedrzejczak, M. F. 2002 Stranded *Zostera marina* L. vs wrack fauna community interactions on a Baltic sandy beach (Hel, Poland): a short-term pilot study. Part II. Driftline effects of succession changes and colonization of beach fauna. *Oceanologia* **44**(3), 367-387.

Komar, 1976. Beach Profiles and Onshore-offshore sediment transport, p. 288-324.

Koop, K. and Lucas, M. I. 1983 Carbon flow and nutrient regeneration from the decomposition of macrophyte debris in a sandy beach microcosm. **In**, *Sandy beaches as ecosystems*, edited by A. McLachlan and T. Erasmus, Junk, The Hague, pp. 249-262.

Kyle, R., Robertson, W. D. and Birnie, S. L. 1997 Subsistence shellfish harvesting

in the Maputaland Marine Reserve in Northern Kwazulu-Natal, South Africa: Sandy Beach Organisms. *Biological Conservation* **82**, 173-182.
Lavery, P., Bootle, S. and Vanderklift, M. 1999 Ecological effects of macroalgal harvesting on beaches in the Peel-Harvey Estuary, Western Australia. *Estuarine, Coastal and Shelf Science* **49**, 295-309.
Lavoie, D. R. 1985 Population dynamics and ecology of beach wrack macroinvertebrates of the Central California Coast. *Bulletin of the Southern California Academy of Science* **84**(1), 1-22.
Leatherman, S. P. and Godfrey, P. J. 1979 The impact of off-road vehicles on coastal ecosystems in Cape Cod National Seashore: An overview. University of Massachusetts-National Park Service Research Unit, Report **34**, 34 pp.
Levene, H. 1960 Robust tests for equality of variance.***In** Contributions to Probability and Statistics*, edited by Olkin et al., Stanford University Press: Stanford, pp. 278-292.
Liddle, M. J. and Greig-Smith, P. 1975 A survey of tracks and paths in a sand dune ecosystem I. Soils. *Journal of Applied Ecology* **12**, 893-908.
Lopez, J. J. 1998 *The use of negotiated rulemaking in piping plover/off-road vehicle management at Cape Cod National Seashore*. Master's Thesis. The University of Rhode Island, 159 pp.
Marsden, I. D. 1991a. Kelp-sandhopper interactions on a sand beach in New Zealand. I. Drift composition and distribution. Journal of Experimental Marine Biology and Ecology **152**: 61-74.
Mathis, W. N. and Munari, L. 1996 World catalog of the Family Tethinidae (Diptera). Smithsonian Contributions to Zoology, Number **584**. Washington, D.C.: Smithsonian Institution Press. 27 pp.
McArdle, S. B. and McLachlan, A. 1992 Sand beach ecology: swash features relevant to the macrofauna. *Journal of Coastal Research* **8**(2): 398-407.
Melander A. L. 1951 The North American species of Tethinidae (Diptera). *Journal of the New York Entomological Society* **59** (4), 187-212.
Melvin, S. M., Hecht, A., and Griffin, C. R. 1994 Piping Plover Mortalities caused by off-road vehicles on Atlantic coast beaches. *Wildlife Society Bulletin* **22**, 409-414.
Moffett, M. D., McLachlan, A., Winter, P. E. D. and De Ruyck, A. M. C. 1998 Impact of trampling on sandy beach macrofauna. *Journal of Coastal Conservation* **4**(1), 87-90.
Moore, P. G. and Francis, C. H. 1985 On the water relations and osmoregulation of the beach-hopper *Orchestia gammarellus* (Pallas) (Crustacea: Amphipoda). *Journal of Experimental Marine Biology and Ecology* **94**, 131-150.
Negotiated Rulemaking Committee 1998 Cape Cod National Seashore; Off-Road Vehicle Use. Final Rule. *Federal Register* **63**, 9143-9149. (63 **FR** 9143-9149).
Negotiated Rulemaking Committee 1998 Cape Cod National Seashore; Off-Road Vehicle Use. Final Rule. *Code of Federal Regulations*, title 36, chapter 1, part 7, section 7.67. (36 **CFR** 7.67)

Nelson, W. G. 1985 *Guidelines for beach restoration projects, Part 1: Biological.* Florida Sea Grant Project No. R/C-4. Report Number **76**. 66 pp.

Ockay, C. and Hubert, J. F. 1996 Mineralogy and provenance of Pleistocene outwash-plain and modern beach sands of outer Cape Cod, Massachusetts, USA. *Marine Geology* **130**, 121-137.

Pennings, S. C., Carefoot, T. H. Zimmer, M, Danko, J. P. and Ziegler, A. 2000 Feeding preferences of supralittoral isopods and amphipods. *Canadian Journal of Zoology* **78**, 1918-1929.

Peterson, C. H., Hickerson, D. H. M. and Johnson, G. G. 2000 Short-term consequences of nourishment and bulldozing on the dominant large invertebrates of sandy beach. *Journal of Coastal Research* **16**(2), 368-378.

Polis, G. A. and Hurd, S. D. 1996 Linking Marine and terrestrial food webs: allochthonous input from the ocean supports high secondary productivity on small islands and coastal land communities. *American Naturalist* **147**, 396-423.

Rakocinski, C. F., Heard, R.W., LeCroy, S.E., McLelland, J. A. and Simons, T. 1996 Responses by macrobenthic assemblages to extensive beach restoration at Perdido Key, Florida, USA. *Journal of Coastal Research* **12**(1), 326-353.

Rickard, C. A., McLachlan, A., and Kerley, G. I. H. 1994 The effects of vehicular and pedestrian traffic on dune vegetation in South Africa. *Ocean & Coastal Management* **23**, 225-247.

Robertson, A. I. and Mann, K. H. 1980 The role of isopods and amphipods in the initial fragmentation of eelgrass detritus in Nova Scotia, Canada. *Marine Biology* **59**, 63-69.

Schoeman, D. S., McLachlan, A. and Dugan, J. E. 2000 Lessons from a disturbance experiment in the intertidal zone of an exposed sandy beach. *Estuarine, Coastal and Shelf Science* **50**, 869-884.

Sidle, J.G. 1984 Piping plover proposed as an endangered and threatened species. *Federal Register* **49**, 44711-44715.

Sidle, J.G. 1985 Determination of endangered and threatened status for the Piping Plover. *Federal Register* **50**, 50726-50733. 50 **FR** 50726.

Sokal, R. R. and F. J. Rohlf. 1995. Biometry: the principles and practice of statistics in biological research. 3rd edition. W. H. Freeman and Co.: New York. 887 pp.

Staine, K. J. and Burger, J. 1994. Nocturnal foraging behavior of breeding piping plovers (*Charadrius melodus*) in New Jersey. *The Auk* **111**(3), 579-587.

Steinback, J. M. K. 1999 The ocean beach invertebrates of Fire Island National Seashore, New York: Spatial and temporal trends and the effects of vehicular disturbance [MS thesis]. Stony Brook (NY): The State University of New York. 252 p.

Steiner, A. J. and S. P. Leatherman. 1981 Recreational impacts on the distribution of ghost crabs *Ocypode quadrata* Fab. *Biological Conservation* **20**, 111-122.

Stephenson, G. 1999 Vehicle impacts on the biota of sandy beaches and coastal

dunes: A review from a New Zealand perspective. *Science for Conservation* **121**, 48 p.
Tenore et al. 1982
U. S. Fish and Wildlife Service. 1985. Determination of endangered and threatened status for the piping plover. *Federal Register* **50** (238): 50,726-50,734.
U. S. Fish and Wildlife Service. 1993. U.S. Fish and Wildlife Service Northeastern beach tiger beetle (*Cicindela dorsalis dorsalis*) recovery plan. Hadley MA.
Van der Merwe, D. and Van der Merwe, D. 1991 Effects of off-road vehicles on the macrofauna of a sandy beach. *South African Journal of Science* **87**, 210-213.
van Senus, P. and McLachlan, A. 1985 Distribution and behavior of the amphipod, *Talorchestia capensis* (Crustacea; Talitridae). *S.-Afr. Tydskr. Dierk*. **20** (4), 252-257.
Visco, C. 1977 *The geomorphic effects of off-road vehicles on the beach, Fire Island, New York*. State University of New York at Binghamton. M. A. Thesis. 74 pp.
Watson, J. J., Kerley, G. I. H., and McLachlan, A. 1996 Human Activity and potential impacts on dune breeding birds in the Alexandria Coastal Dunefield. *Landscape and Urban Planning* **34**, 315-322.
Weslawski, J. M., Stankek, A., Siewert, A. and Beer, N. 2000a The Sandhopper (*Talitrus saltator*, Montagu 1808) on the Polish Baltic Coast. Is it a victim of increased tourism? *Oceanological Studies* **29** (1), 77-87.
Weslawski, J. M., Urban-Malinga, B., Kotwicki, L., Opalinski, K., Szymelfenig, M., Dutkowski, M. 2000b Sandy Coastlines-are there conflicts between recreation and natural values? *Oceanological Studies* ***29*** (2), 5-18.
Wheeler, N. R. 1979 *Effects of off-road vehicles on the infauna of Hatches Harbor, Cape Cod National Seashore.* University of Massachusetts-National Park Service Research Unit, Report **28**, 47 pp.
Wolcott, T. G. and Wolcott, D. L. 1984 Impact of Off-Road Vehicles on Macroinvertebrates of a Mid-Atlantic Beach. *Biological Conservation* **29**, 217-240.
Wright, L. D. and Short, A. D. 1983. Morphodynamics of beaches and surf zones in Australia. In P.D. Komar (Ed.), CRC Handbook Coastal Processes and Erosion, CRC Press, London, pp 35-64.
Yaninek, J.S. 1980. Beach wrack: Phenology of an imported resource and utilization by macroinvertebrates of sandy beaches. M.A. Thesis. Dept. of Zoology, University of California, Berkeley. 159pp.
Zaremba, R., Godfrey, P. J., and Leatherman, S. P. 1979 *The ecological effects of off-road vehicles on the beach/backshore zone in Cape Cod National Seashore, Massachusetts.* University of Massachusetts-National Park Service Research Unit, Report **28**, 67 pp.

Table 1 Background characteristics for the four sampled beaches with vehicle access and the Ballston area where the manipulative experiment study

	Wave height (m)	Tidal range (m)	Back Beach	Morphology	Exposure	Median grain size (mm)	Longshore drift	Latitude	Longitude
Cape Cod National Seashore									
Race Point North	1.05-1.25	2-4	moderate dunes (3 m); densely vegetated foredunes	barrier spit	N	1-1.2	W	42º 04’ 46.92” W	70º 13’ 23.16" N
Race Point South	1.05-1.25	2-4	moderate dunes (4-6 m); eroding dune face	barrier spit	N	1-1.2	W	42º 04’ 53.22" W	70º 12’ 47.16" N
Coast Guard	>1.25	2-4	eroding sea cliffs (16-18 m); north of cut has densely vegetated foredune	glacial outwash	NE	.85-1	NW	42º 02’ 54.96" W	70º 00’ 24.12" N
Ballston Beach	>1.25	2-4	eroding sea cliffs (30 m)	glacial outwash	E	.85-1	N	41º 58’ 54.12" W	70º 00’ 24.12" N
Fire Island National Seashore									
Sailor's Haven	>1.25	<1.0	low dunes (1 m); densely vegetated foredunes	barrier island	S	.2-.4	W	40º 39’ 09.16” W	73º 07’ 08.01” N

Table 2 Selected environmental variables measured for wrack/core samples and along whole beach transects within traffic and non-traffic areas of Cape Cod National Seashore during the 2001 field season. An X under the P value indicates that significant 3-way interactions of treatment ***x*** site ***x*** period rendered the 3-way ANOVA invalid. An @ indicates that site means were significantly different at the 0.05 value.

Cape Cod 2001: AVERAGED ENVIRONMENTAL VARIABLES FOR ALL THREE SITES

Within sample quadrats	CG-NT	CG-T	RPS-NT	RPS-T	RPN-NT	RPN-T	All Sampling sites		F-value	df	P
% Cover of sample wrack in quadrat	44.5 +/- 2.7	32.5 +/- 10.7	69.5 +/- 3.0	56.0 +/- 17.7	62.0 +/- 5.2[@]	36.5 +/- 11.5	58.7 +/- 3.9	41.7 +/- 13.2	8.9	1, 44	0.004
Wrack volume (l) per sample	1.3 +/- 0.4	1.0 +/- 0.3	2.4 +/- 0.5	1.9 +/- 0.5	1.4 +/- 0.2	1.0 +/- 0.2	1.7 +/- 0.2	1.3 +/- 0.2	1.8	1, 44	0.19
Wrack dry weight (gm) per wrack sample	115 +/- 47	90 +/- 33	307 +/- 71	333 +/- 136	141 +/- 22	112 +/- 31	193 +/- 33	185 +/- 53	0.02	1, 44	0.90
Average % moisture loss per wrack sample	20.1 +/- 3.0	31.5 +/- 5.6	22.8 +/- 4.0	24.7 +/- 3.2	16.5 +/- 2.4	25.3 +/- 4.5[@]	19.8 +/- 1.9	26.8 +/- 2.5	7.1	1,44	0.01
Mean ranking of wrack age (1-fresh, 2-decaying, 3-old, 4-very old)	2.2 +/- 0.4	2.3 +/- 0.4	3.0 +/- 0.3	2.9 +/- 0.4	3.2 +/- 0.4	3.4 +/- 0.5	2.8 +/- 0.2	2.9 +/- 0.3	0.04	1,48	0.85
Relative humidity (%) at wrack/sand interface	74.9 +/- 2.7	81.0 +/- 2.6	85.0 +/- 3.0	84.0 +/- 2.9	80.2 +/- 5.2	76.2 +/- 6.6	80.0 +/- 2.3	80.4 +/- 2.6	0.02	1,48	0.89
Sample temperature (°C) at wrack/sand interface	28.6 +/- 1.7[@]	21.9 +/- 0.9	23.6 +/- 1.4	29.7 +/- 1.4[@]	27.5 +/- 1.3	28.5 +/- 2.5	26.6 +/- 0.9	26.7 +/- 1.2	0.22	1,48	**X**
Sample distance (m) from dune vegetation	11.4 +/- 2.2	13.1 +/- 2.3	19.2 +/- 3.3	22.7 +/- 1.0	12.9 +/- 1.7	15.6 +/- 3.8	14.9 +/- 1.6	17.1 +/- 1.0	1.8	1,48	0.19
On the whole beach											
Average elliptical surface area per wrack clump (m^2)	0.40 +/- 0.10[@]	0.04 +/- 0.01	0.50 +/- 0.1	0.47 +/- 0.1	0.18 +/- 0.02	0.27 +/- 0.1	0.38 +/- 0.05	0.34 +/- 0.03	2.4	1,1168	**X**
Average density (m^3) $*10^{-3}$ per wrack clump	5 +/- 1[@]	2 +/- 0.3	5 +/- 1	7 +/- 1	5 +/- 1	5 +/- 1	5 +/- 1	6 +/- 1	0.05	1,1168	0.82
Mean ranking for consistency of thickness (1-low, 2-medium, 3-high, 4-very high)	2.0 +/- 0.1[@]	1.7 +/- 0.1	2.2 +/- 0.1[@]	1.9 +/- 0.1	2.2 +/- 1.0	2.2 +/- 1.0	2.2 +/- 0.1	1.9 +/- 0.1	7.3	1,1142	0.007
Average density (m^3) per meter^2 of beach $*10^{-3}$	1 +/- 0.3[@]	0.2 +/-0.1	2.7 +/- 0.7	2.4 +/- 0.4	1 +/-0.3	0.9 +/- 0.2	1.7 +/- 0.3	1.2 +/- 0.2	7.3	1,48	**X**
Estimated % cover for 100m sample area	1.9 +/- 0.4[@]	0.6 +/- 0.2	1.5 +/- 0.2	1.6 +/- 0.2	3.4 +/- 1.2	2.9 +/- 1.0	2.3 +/- 0.4	1.7 +/- 0.4	4.6	1,48	0.04

	WRACK		CORE		PITFALL		% of
	NT	T	NT	T	NT	T	total
Oligochaeta: *Enchytraeidae sp.*	34 +/-16	37 +/-15	15 +/-9	16 +/-4	0.5 +/-0.4	2.6 +/-1.7	40.1%
Tethinidae: *Tethina parvula*	3.9 +/-1.5	8.3 +/-3.6	4.6 +/-1.3	5.6 +/-1.8	2.3 +/-0.7	4.8 +/-2.1	11.4%
% larvae/pupae	88%	94.0%	95%	90%	97%	99%	
% adults	12%	6%	5%	10%	3%	1%	
Hydrophilidae: *Cercyon littoralis*	5.9 +/-0.3	2.4 +/-0.9	15 +/-14	0.9 +/-0.5	0.2 +/-0.1	0.2 +/-0.1	9.2%
% adults	98%	92%	97.5%	58%	100%	100%	
% larvae	2%	8%	2.5%	42%	0	0	
Sphaeroceridae: *Thoracochaeta*	0.2 +/-0.2	2.6 +/-1.9	0.9 +/-0.8	0.1 +/-0.1	0.9 +/-0.5	0.4 +/-0.2	2.0%
brachystoma % adults	0	100%	4%	100%	100%	100%	
% larvae/pupae	100%	0	96%	0	0	0	
Staphylinid: *undetermined spp.*	1.6 +/-0.9	0.6 +/-0.3	1.0 +/-0.4	0.3 +/-0.1	0.1 +/-0.1	0	1.4%
Anthomyiidae: *Fucellia tergina*	0.4 +/-0.1	2.0 +/-1.6	0.2 +/-0.1	0.9 +/-0.5	0.5 +/-0.3	0.1 +/-0.1	1.6%
% larvae	60%	91%	40%	69%	0	25%	
% adults	30%	1.8%	0	0	100%	75%	
% pupae	10%	7%	60%	31%	0	0	
Anthicidae: *undetermined sp.*	1.1 +/-0.4	0.6 +/-0.3	0.2 +/-0.1	0.04 +/-0.04	0.2 +/-0.2	0.3 +/-0.2	1.0%
Amphipoda: *Talorchestia*	1.5 +/-0.9	0.1 +/-0.1	1.9 +/-1.1	0	21 +/-6	0.9 +/-0.5	10.3%
longicornis < than 14 mm	98%	100%	93%	0	30%	50%	
mature	2%	0	7%	0	70%	50%	
Talorchestia megalopthalma	0	0	0	0.1 +/-0.1	2.0 +/-2.0	2.9 +/-2.0	2.7%
Lycosidae: *Arctosa littoralis*	0.3 +/-0.1	0.1 +/-0.1	0	0	1.3 +/-0.4	0.2 +/-0.1	0.6%
Histeridae: *Hypocaccus fraternus*	0.2 +/-0.1	0.1 +/-0.1	0.4 +/-0.3	0.3 +/-0.2	3.1 +/-0.7	1.4 +/-0.4	2.3%
Ephydridae: *Hecamede albicans*	0	0.5 +/-0.2	0.1 +/-0.1	0.4 +/-0.3	0.3 +/-0.2	0.7 +/-0.3	0.8%
% adults	0	61.5%	0	10%	100%	100%	
% pupae	0	38.5%	100%	90%	0	0	
Tenebrionidae: *Phaleria testacea*	0.3 +/-0.2	0.1 +/-0.1	0.6 +/-0.3	0.04 +/-0.04	0.2 +/-0.2	0	0.5%
% larvae	75%	50%	50%	100%	50%	0	
% adults	25%	50%	50%	0	50%	0	
Empididae: *Chersodromia inusitata*	0.04 +/-0.04	0.1 +/-0.1	0	0	0.2 +/-1.0	0.5 +/-0.2	0.3%
Others	9.9 +/-1.1	7.1 +/-1.2	6.9 +/-0.9	4.3 +/-0.6	9.8 +/-1.1	5.6 +/-1.2	15.9%
Totals	**1656**	**1720**	**1300**	**800**	**1227**	**612**	**7315**
# of listed species	**12 of 31**	**13 of 37**	**11 of 30**	**11 of 29**	**14 of 50**	**12 of 52**	**79**

Table 3 Average abundances per sample of dominant taxa; wrack/core and pitfall trap samples at the three CACO study sites in 2001.

Variable Measured	Treatments			P-value
	Control	Low-traffic	High-traffic	
Bag dimensions (cm^3)	1521 ± 84	920 ± 96	881 ± 90	<.001
Temperature (°C) at the wrack/sand interface	27.2 ± 1.0	27.3 ± 1.0	27.9 ± 1.1	0.88
Relative humidity (%) at the wrack/sand interface	69.3 ± 1.8	70.4 ± 2.5	70.1 ± 2.2	0.94
Temperature (°C) at 10cm depth	23.8 ± 0.5	23.7 ± 0.4	23.9 ± 0.4	0.96
Percentage of wrack clumps fully buried	11.1	40.7	40.7	0.02

Table 4 Environmental variables measured from high-, low- and control treatment bags in the direct impact study. Days were grouped into three periods, and two-way ANOVAs (treatment*period) were performed.

Figure Legends

Figure 1 Mean # of vehicles using the beach, June-August, as measured by Cuesta Systems TS-601 traffic broken-beam traffic counters installed by the NPS at access points to each driven sample area. SH, FI count was estimated by transect counts of observed vehicle tracks in the sampling area.

Figure 2 Average Race Point North profiles for traffic and non-traffic areas calculated by averaging transect elevations from sampling period 1. Note that the averaged profile slope depicted here varies somewhat from the calculation for slope averaged from the five original transects

Figure 3 Average Race Point South profiles for traffic/non-traffic areas calculated by averaging transect elevations from sampling period 1. Note that the averaged profile slope depicted here varies somewhat from the calculation for slope averaged from the five original transects

Figure 4 Average Coast Guard profiles for traffic and non-traffic areas calculated by averaging transect elevations from sampling period 1. Note that the averaged profile slope depicted here varies somewhat from the calculation for slope averaged from the five original transects

Figure 5 Average Sailor's Haven profiles for traffic and non-traffic areas calculated by averaging transect elevations from sampling period 2. Note that the averaged profile slope depicted here varies somewhat from the calculation for slope averaged from the five original transects

Figure 6 Comparison of mean wrack frequency within traffic/non-traffic areas on CACO beaches: along the entire beach width (the end of vegetation from to the swash at low tide), indicated by histogram, and within the ORV corridors or their projected location if driving had occurred (●).
Wrack frequency per meter^2 (3-way ANOVA): Treatment: F=16.2 df=1, 48 P<0.001;
Site*Period interaction: F= 73.4 df=2, 48 P<0.001; Site: F=29.0 df=1, 48 P<0.0001;
Period: F=74.4 df=1, 48 P<0.001.
Wrack occurring in traffic corridor (2-way nonparametric Scheirer-Ray-Hare ANOVAs were run at each site separately due to heterogeneous variances): Treatment at CG site: F=6.7 df=1,16 P=0.02; at RPS site: F=22.6 df=1,16 P<0.002; and at RPN site: F=5.2 df=1,16 P=0.04.

Figure 7 Average wrack/core abundances from **a)** Sailor's Haven, Fire Island in 1995, and from **b)** Cape Cod beaches in 2001. ANOVA results are based on log (X+1) transformed data. No periods are significant by themselves at SH.

Site*period (F=7.2 df=1, 56 P=0.01) and site (F=5.0 df=1, 44 P=0.01) are significant for Cape Cod, but no sites are significant by themselves

Figure 8 Average pitfall trap abundances from **a)** Sailor's Haven, Fire Island in 1995, and from Cape Cod beaches in **b)** 2001 and **c)** 2002. ANOVA results are based on log (X+1) transformed data. At Fire Island, period is significant (F=28.8 df=2, 58 P<0.001). In both 2001 & 2002, abundances at Cape Cod vary significantly by site (2001: CG & RPN, Ps<0.05; 2002: RPS, P<0.05).
2001 means, MSwithin at CG: 0.14*, RPS: 0.12, and RPN: 0.05* df=18 n=10.
2002 means: MSwithin at CG: 0.21, RPS 0.06*, and RPN: 0.07 df=22 n=12.

Figure 9 Average wrack/core abundances for the amphipod *Talorchestia longicornis* (Talitridae) at **a)** Fire Island and **b)** Cape Cod. Two-way ANOVA (Treatment*sampling period) for Fire Island log (X+1) transformed abundances: Treatment: F=1.1 df=1, 56 P=0.30; Site: F=4.2 df=2, 56 P=0.02. No periods are significant by themselves at SH. Three-way ANOVA for Cape Cod log (X+1) abundances: Treatment: F=6.3 df=1, 44 P=0.02. No sites are significant by themselves, MSwithin=50.2, 98.8, 0.05 k=2 n=10.

Figure 10 Average pitfall trap abundances for the amphipod *Talorchestia longicornis* (Talitridae) at **a)** Fire Island and at Cape Cod in **b)** 2001 and **c)** 2002. Two-way ANOVA (Treatment*sampling period) for Fire Island log (X+1) abundances: Treatment: F=1.2 df=1, 58 P=0.29; Period: F=28.8 df=2, 58 P<0.001. Three-way ANOVA (Traffic* location*period) for Cape Cod log (X+1) abundances in 2001: Treatment: F=85.0, df=1,48 p<<0.001, Traffic*site: F=14.3 df=1, 48 P<0.0001. All site means have Ps<0.05, MSwithin= 0.0.14*, 0.12*, 0.04* k=2 n=10. In 2002: Treatment: F=23.5 df=1, 60 P<0.0001; site: F=21.5 df=2,60 P<0.0001. All site means have Ps<0.05, MSwithin=0.35*, 0.15*, 0.06* k=2 n=12.

Figure 11 Average wrack/core abundances for the common sandy beach wolf spider *Arctosa* in **a)** Fire Island (Two-way ANOVA on log (X+1) transformed abundances, Treatment: F=9.6 df=1, 56 P=0.01; Period: F=0.01 df=2, 56 P=0.73) and **b)** Cape Cod wrack/core samples (Three-way ANOVA on log (X+1) transformed abundances): Treatment: F= 4.1 df=1,44 P<0.05; Site: F=3.4 df=2, 56 P= 0.04).

Figure 12 Average abundances for the common sandy beach wolf spider *Arctosa littoralis* (Lycosidae) in **a)** Fire Island pitfall traps and Cape Cod **b)** 2001 and **c)** 2002 pitfall traps. At Fire Island, a two-way ANOVA (traffic*period) was run on log (X+1) transformed data: Treatment: F=9.4 df=1, 58 P=0.003.

(Kruskal-Wallis one-way ANOVAs were run for each period at Fire Island, as variances were not homogeneous and sample sizes were unequal. Fire Island Period 1, treatment: H =2.3 n=10 df =1 P=0.13. Period 2*, treatment: H=4.8 n=10 df=1 P=0.03. Period 3, treatment: H=2.4 n=12 df=1 P=0.12.

In 2001, a three-way ANOVA (traffic*location*period) for Cape Cod log (X+1) transformed abundances was performed: Treatment: F=19.5 df=1,48 P<0.0001, site*period interaction: F=3.8 df=2, 48 P=0.03, period: F=12.6 df=2,48 P<0.001.

(Two-way Scheirer-Ray-Hare anovas for ranked data performed by site: CG* treatment: H=4.8 df 1,16 P=0.03, period H=6.2 P=0.01. RPS* treatment: H=4.8 df=1,16 P=0.03, period H=4.5 P=0.03. RPN treatment: H=0.69 df=1,16 P=0.4, period H=7.4 P<0.007.)

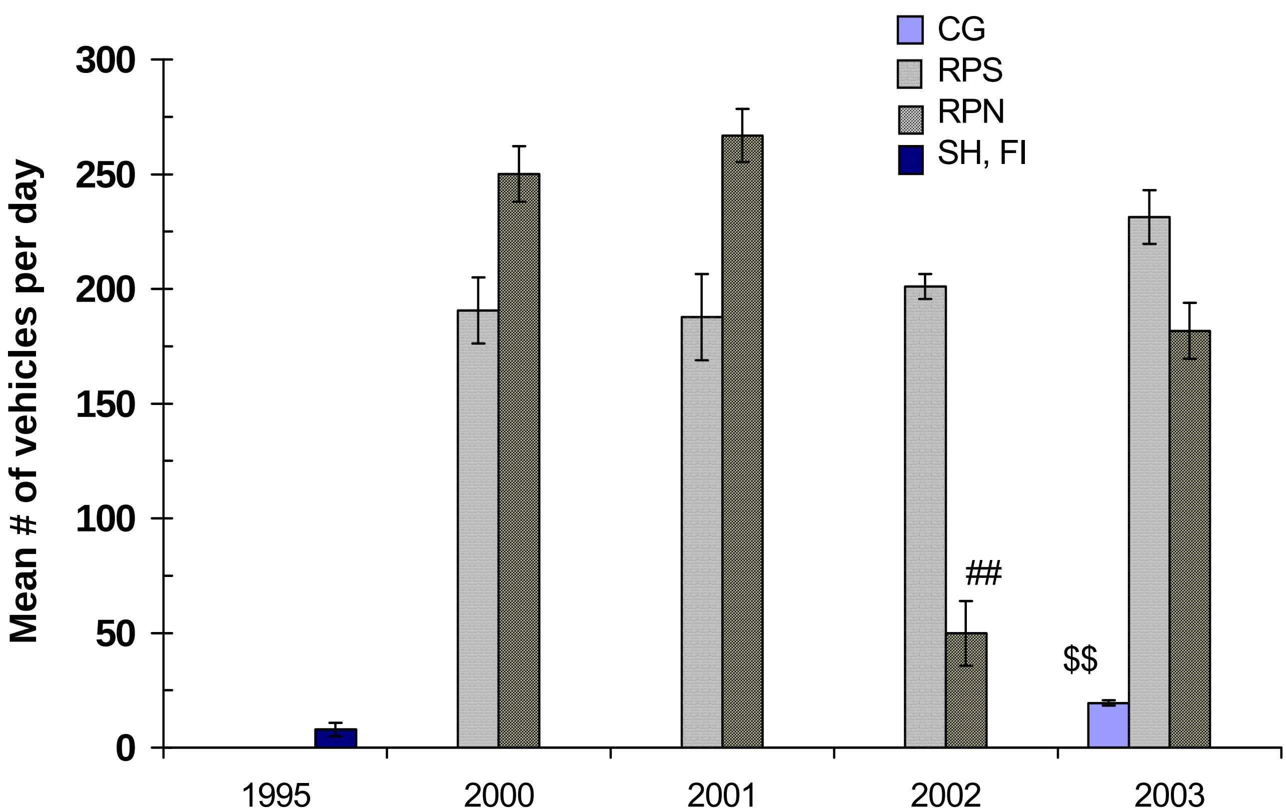
In 2002, Two-way nonparametric Scheirer-Ray Hare ANOVAs were run for ranked data from each site, because variances were not homogeneous. CG treatment is not significant: H=0.75 df=1, 20 n=6 P=0.4, period H=3.9 P=0.05. RPS and RPN have significant treatment*period interactions (H=7.7 df=1, 20 n=6 P<0.005 and H=8.7 df=1, 20 P=0.003), but treatment is significant at both, using T unplanned comparison of means: MSwithin at RPS= 0.01* k=2 n=12 and at RPN=0.02* k=2 n=12.

Figure 13 Average abundances for the east coast dipteran *Tethina parvula* (Tethinidae) in **a)** Fire Island pitfall traps (Two-way ANOVA on log (X+1) transformed abundances, Treatment: F=0.005 df=1, 58 P=0.94; Period: F=4.3 df=2, 58 P=0.02) and **b)** Cape Cod wrack/core samples (Three-way ANOVA on log (X+1) transformed abundances): Treatment: F=0.001 df=1, 48 P=0.98; Site: F=7.2 df=2, 48 P=0.002).

Figure 14 Average abundances for the east coast dipteran *Tethina parvula* (Tethinidae) in Cape Cod pitfall trap samples in **a)** 2001 (Three-way ANOVA on log (X+1) transformed data): Treatment: F=2.4 df=1, 48 P=0.13 and **b)** 2002: Treatment: F=0.002 df=1, 60 P=0.97; Site: F=4.2 df=1, 60 P=0.02; Period: F=23.2 df=2, 60 P<0.001.

Figure 15 Manipulative study
a) Invertebrate abundances within wrack bags over time. Days were grouped into three periods, and a two-way ANOVA (treatment*period) was performed. Treatment effect: F=2.7 df=2, 72 P=0.07.
*indicates an abundance of Tethinid sp. larvae (23% of sample) found in the high-traffic area during the third period.
b)*Phaleria testaceae* (Tenebrionidae) larval abundances within wrack bags over time. A two-way ANOVA (treatment*period) was performed on log (X+1) transformed data. Treatment effect: F=4.8 df=2, 72 P=0.01.

Figure 1



CG
RPS
RPN
SH, FI
Mean # of vehicles per day
300
250
200
150
100
50
0
##
$$
1995
2000
2001
2002
2003

Figure 2

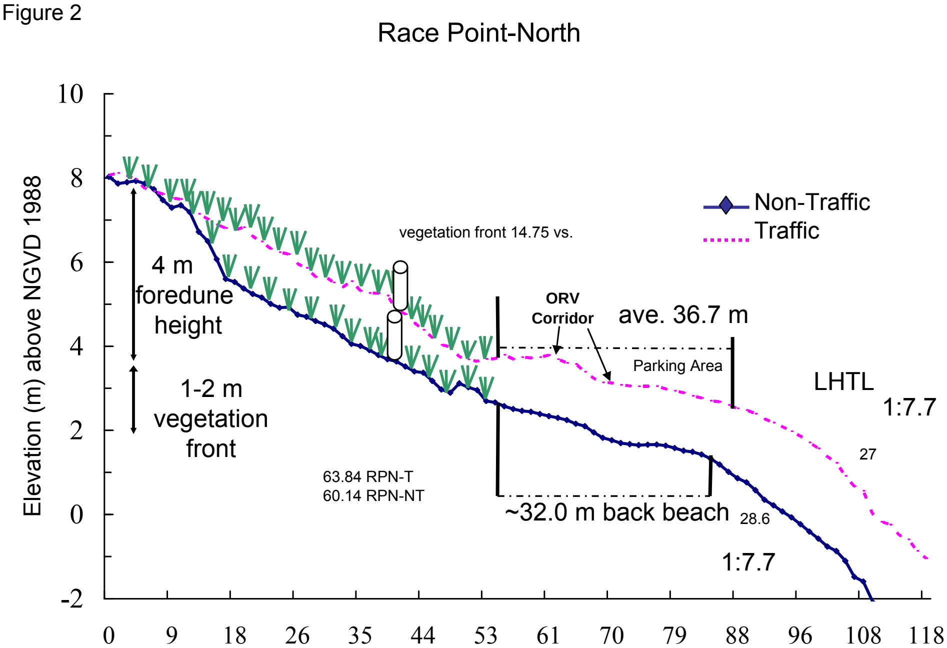
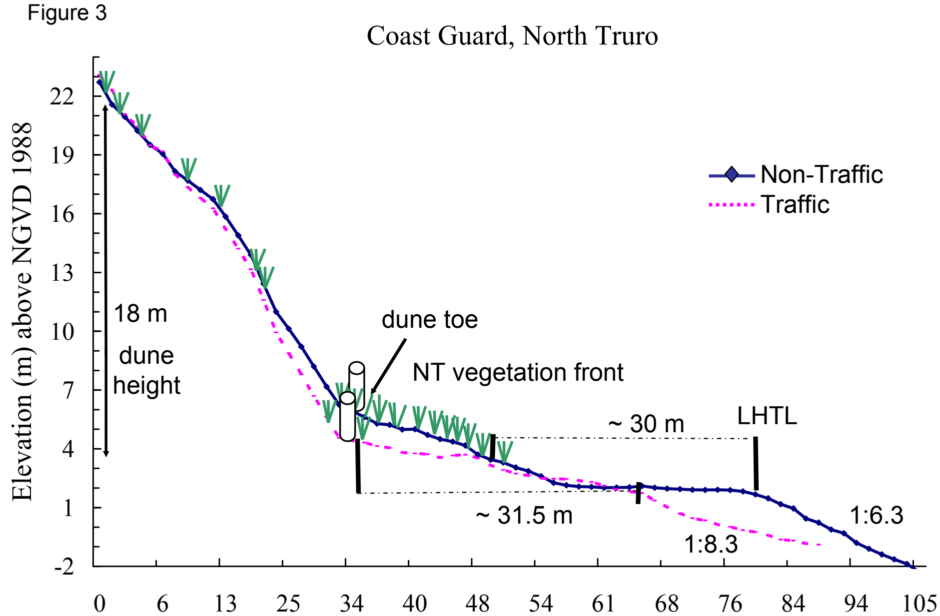
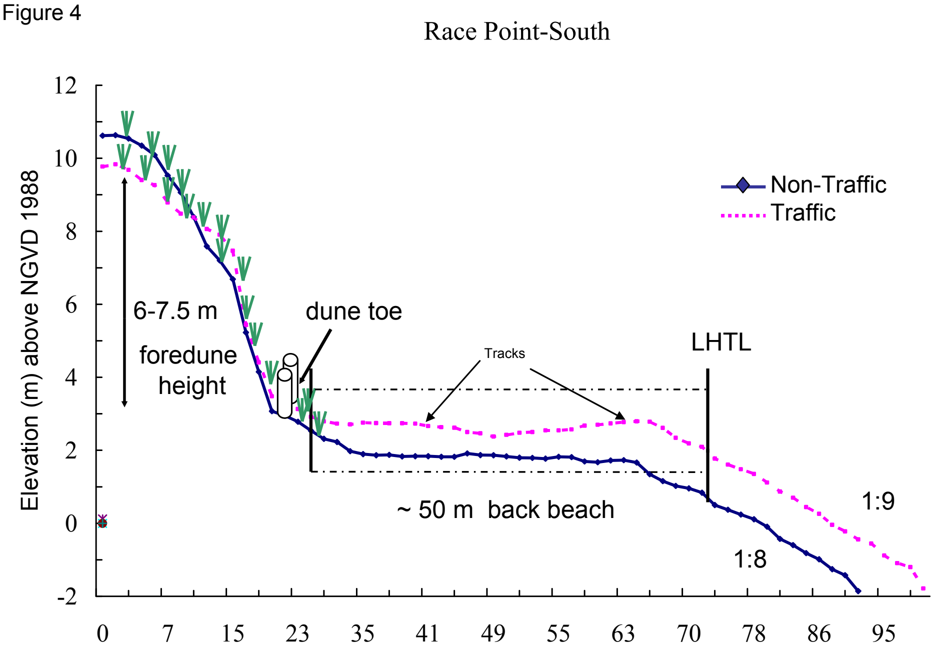

Race Point-North
Elevation (m) above NGVD 1988
10
8
6
4
2
0
-2
0
9
18
26
35
44
53
61
70
79
88
96
108
118
Non-Traffic
Traffic
4 m foredune height
1-2 m vegetation front
vegetation front 14.75 vs.
63.84 RPN-T
60.14 RPN-NT
ORV Corridor
ave. 36.7 m
Parking Area
LHTL
1:7.7
27
~32.0 m back beach
28.6
1:7.7

Figure 3



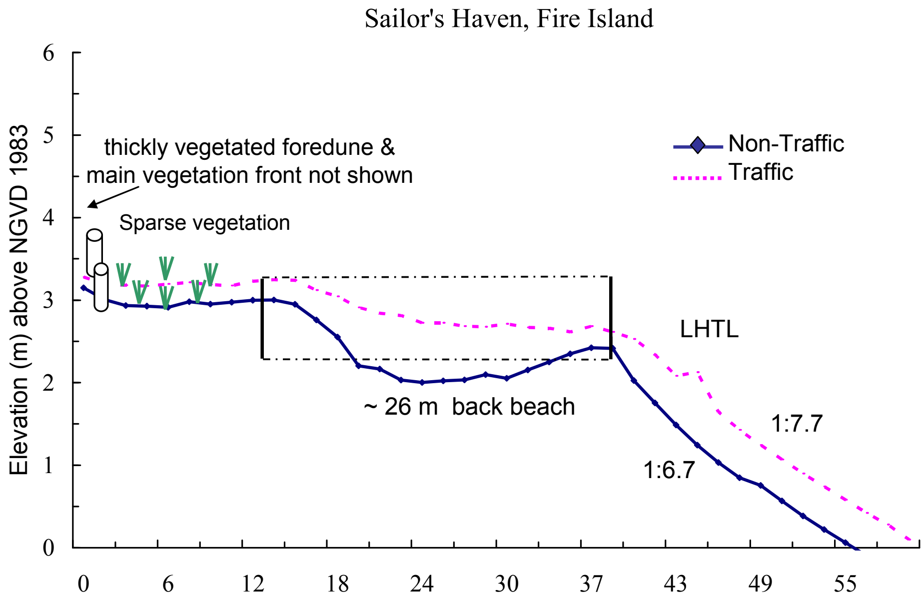
Coast Guard, North Truro
Elevation (m) above NGVD 1988
22
19
16
13
10
7
4
1
-2
0
6
13
25
34
40
48
54
61
68
76
84
94
105
Non-Traffic
Traffic
18 m
dune
height
dune toe
NT vegetation front
~ 30 m
LHTL
~ 31.5 m
1:6.3
1:8.3

Figure 4



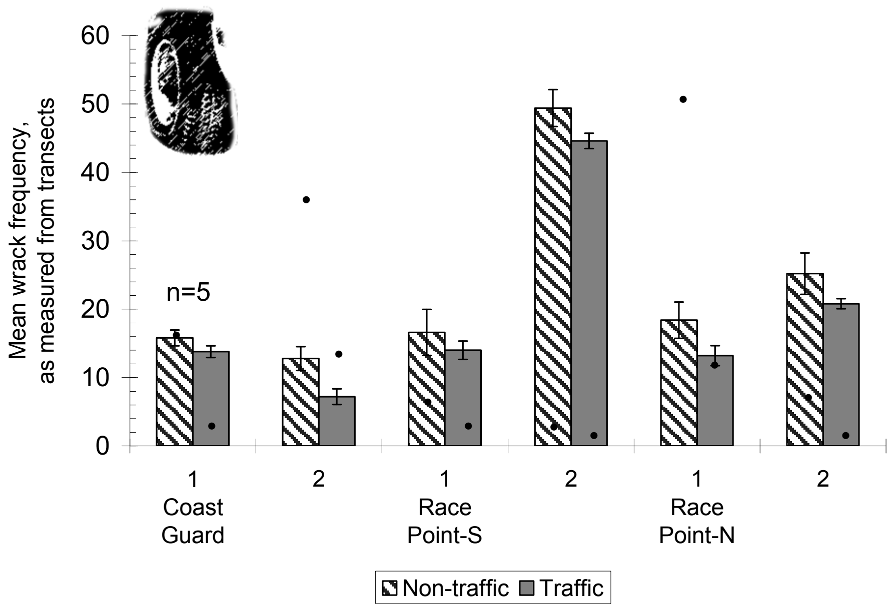
Race Point-South
Elevation (m) above NGVD 1988
12
10
8
6
4
2
0
-2
0
7
15
23
35
41
49
55
63
70
78
86
95
Non-Traffic
Traffic
6-7.5 m
foredune
height
dune toe
Tracks
LHTL
~ 50 m back beach
1:9
1:8

Figure 5



Sailor's Haven, Fire Island
Elevation (m) above NGVD 1983
6
5
4
3
2
1
0
0
6
12
18
24
30
37
43
49
55
thickly vegetated foredune &
main vegetation front not shown
Sparse vegetation
Non-Traffic
Traffic
LHTL
~ 26 m back beach
1:7.7
1:6.7

Figure 6



Mean wrack frequency, as measured from transects
60
50
40
30
20
10
0
n=5
1
Coast Guard
2
1
Race Point-S
2
1
Race Point-N
2
Non-traffic
Traffic

Figure 7

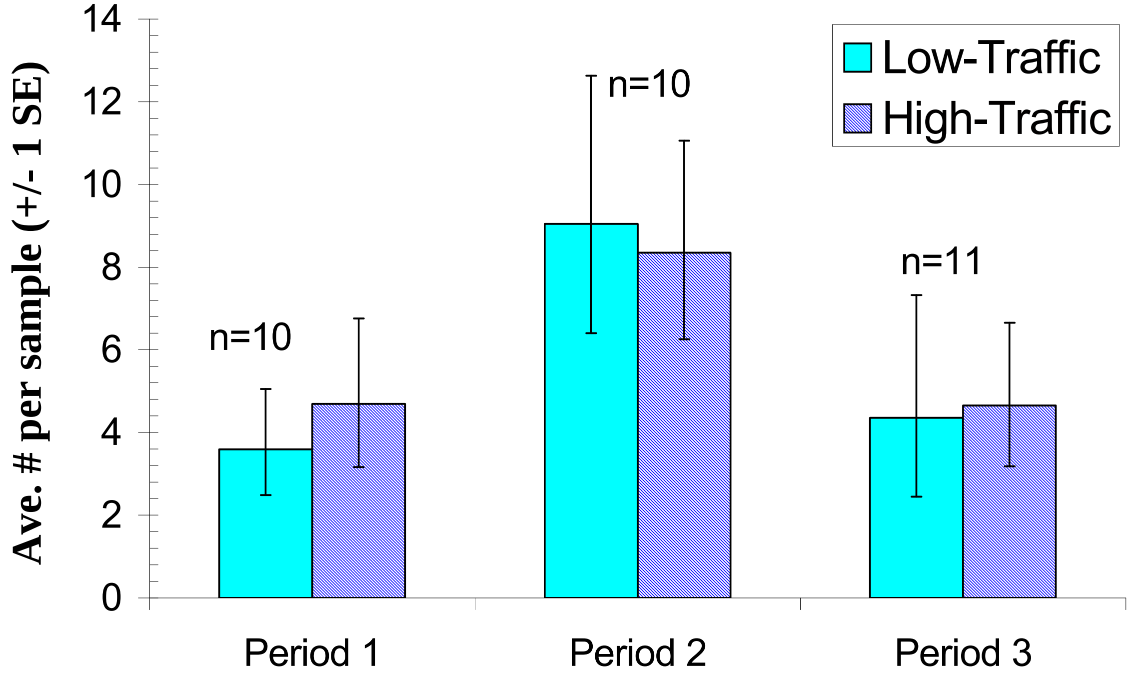
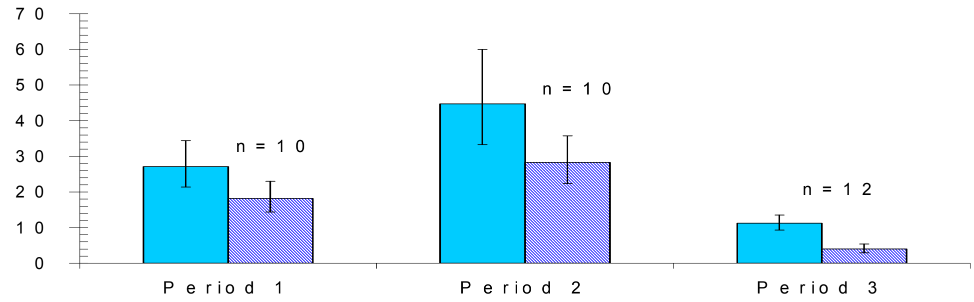

14
12
10
8
6
4
2
0
Ave. # per sample (+/- 1 SE)
Low-Traffic
High-Traffic
n=10
n=10
n=11
Period 1
Period 2
Period 3

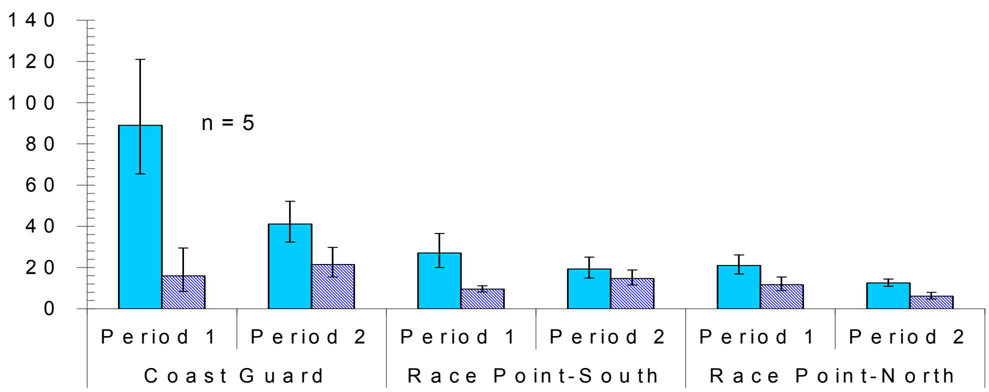
Figure 8

A



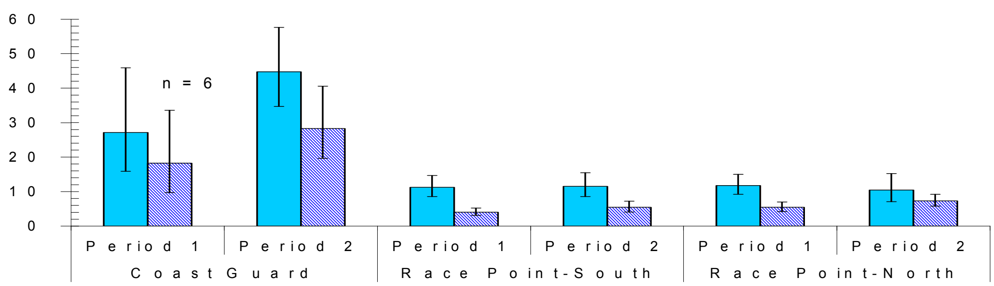
70
60
50
40
30
20
10
0
n = 10
n = 10
n = 12
Period 1
Period 2
Period 3

B



140
120
100
80
60
40
20
0
n = 5
Period 1
Period 2
Period 1
Period 2
Period 1
Period 2
Coast Guard
Race Point-South
Race Point-North

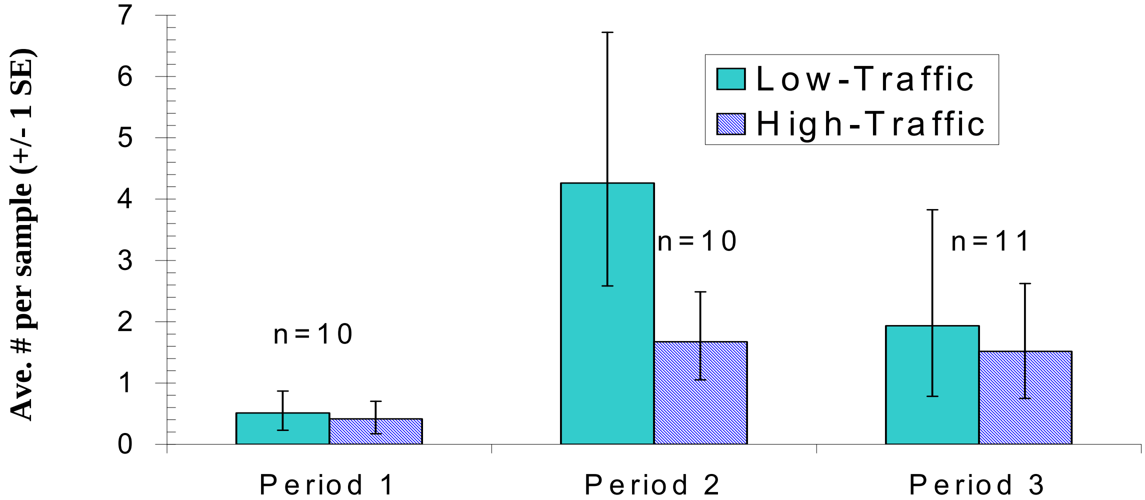
C



60
50
40
30
20
10
0
n = 6
Period 1
Period 2
Period 1
Period 2
Period 1
Period 2
Coast Guard
Race Point-South
Race Point-North

Figure 9

A. Sailor's Haven



B. Cape Cod

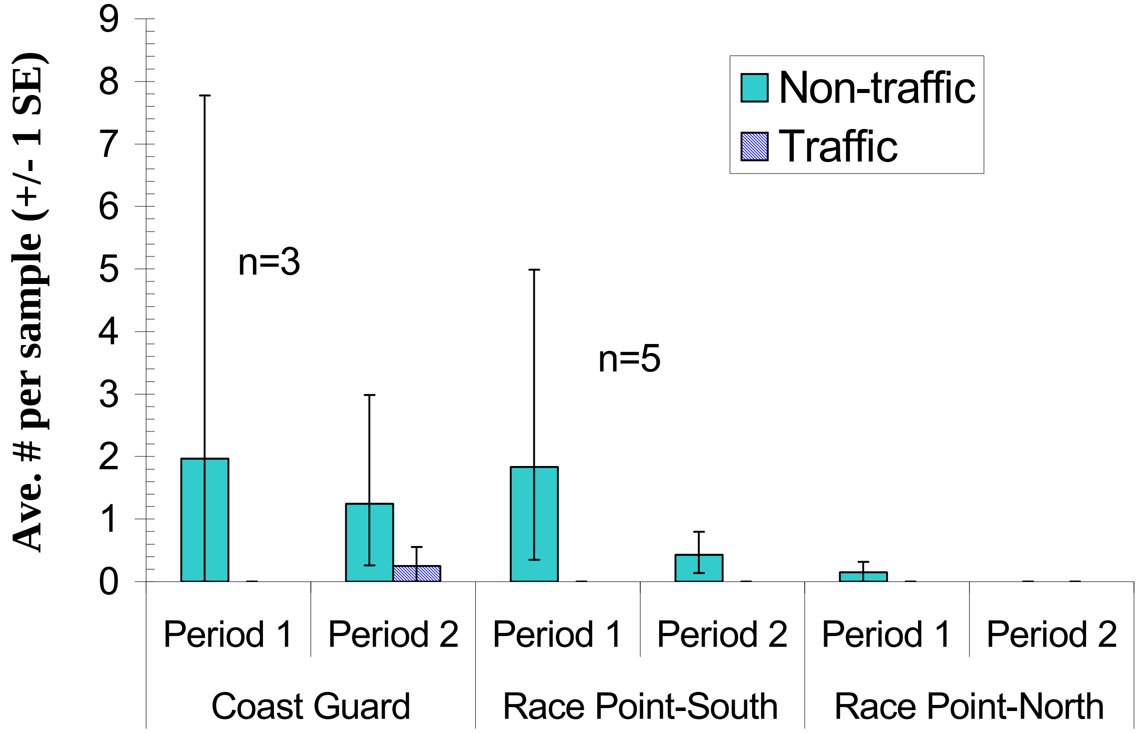
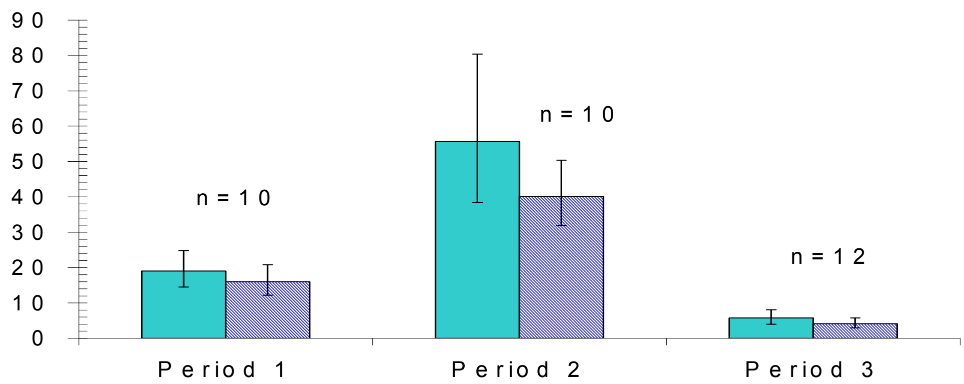
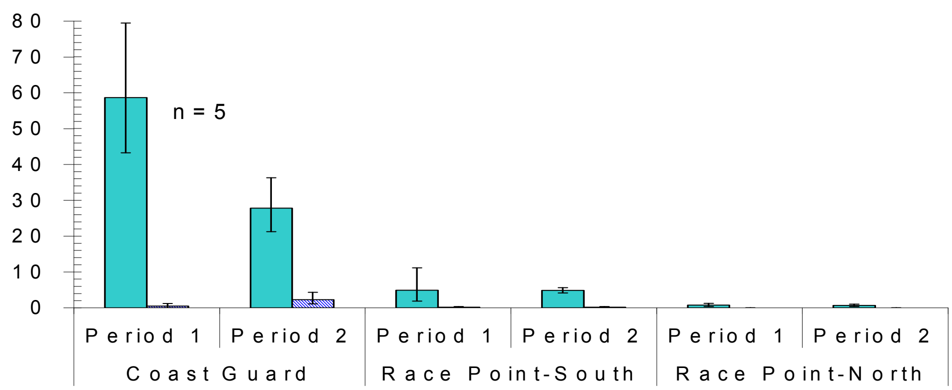


Figure 10

A. Fire Island pitfall traps, 1995



B. Cape Cod pitfall traps, 2001



C. Cape Cod pitfall traps, 2002

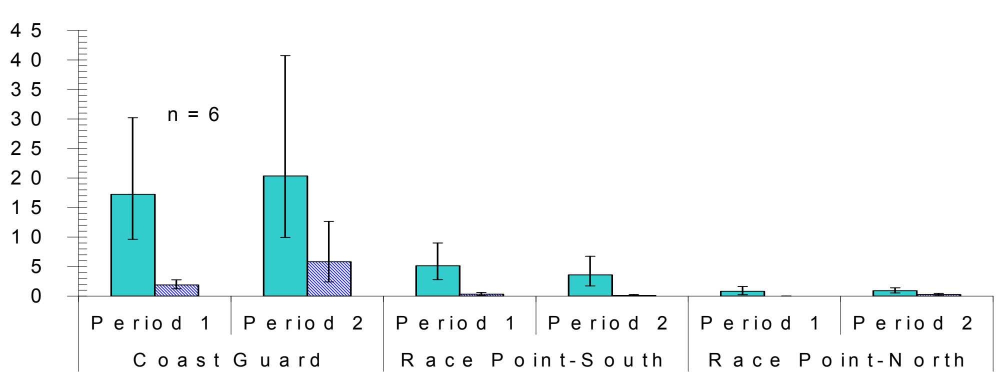
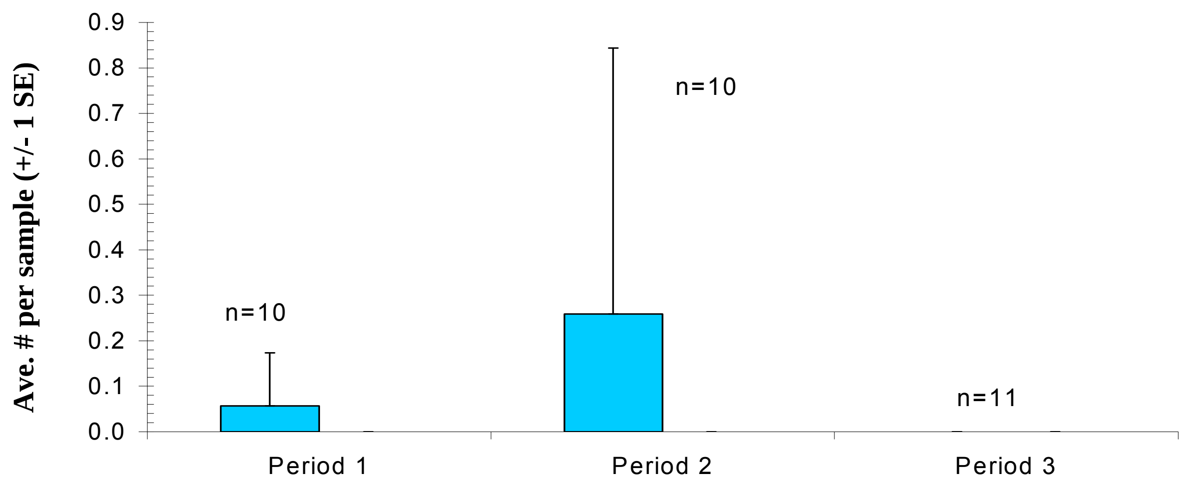


Figure 11

A. Sailor's Haven, wrack/core samples



B. Cape Cod, wrack/core samples

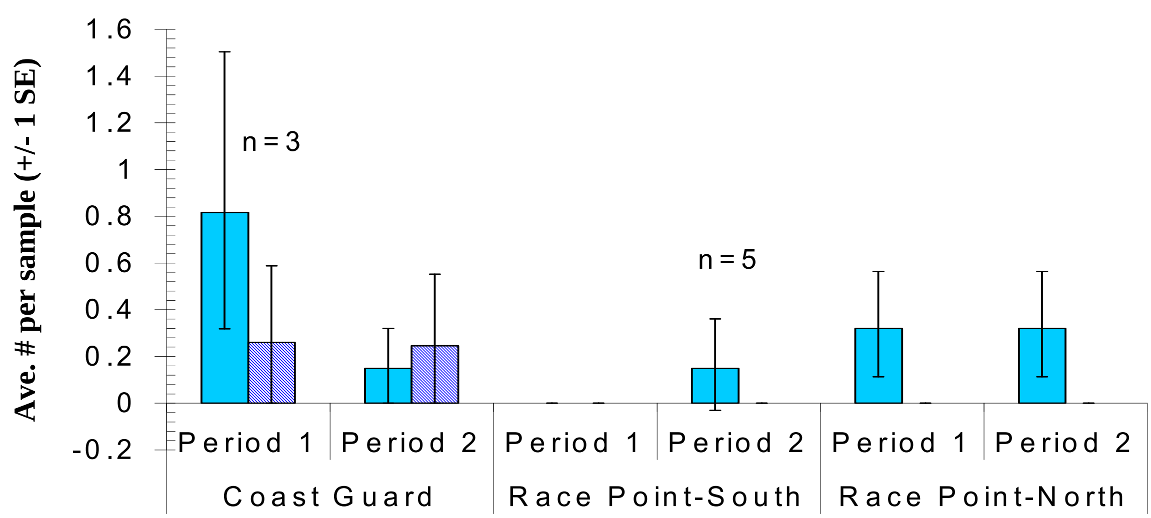
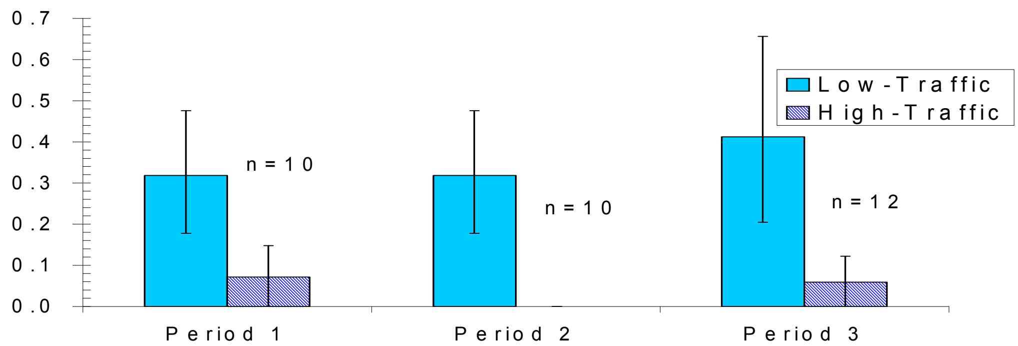
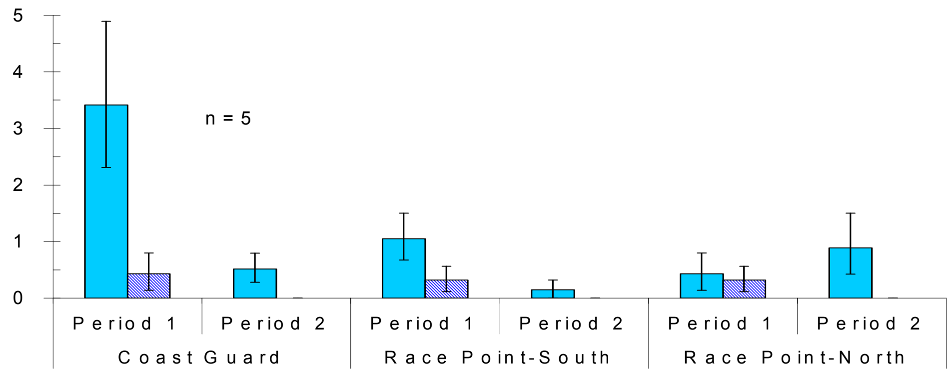


Figure 12

A. Fire Island pitfall traps, 1995



B. Cape Cod pitfall traps, 2001



B. Cape Cod pitfall traps, 2002

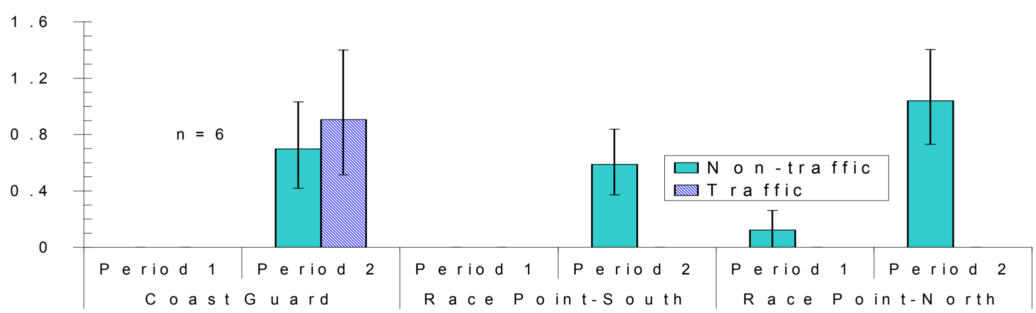
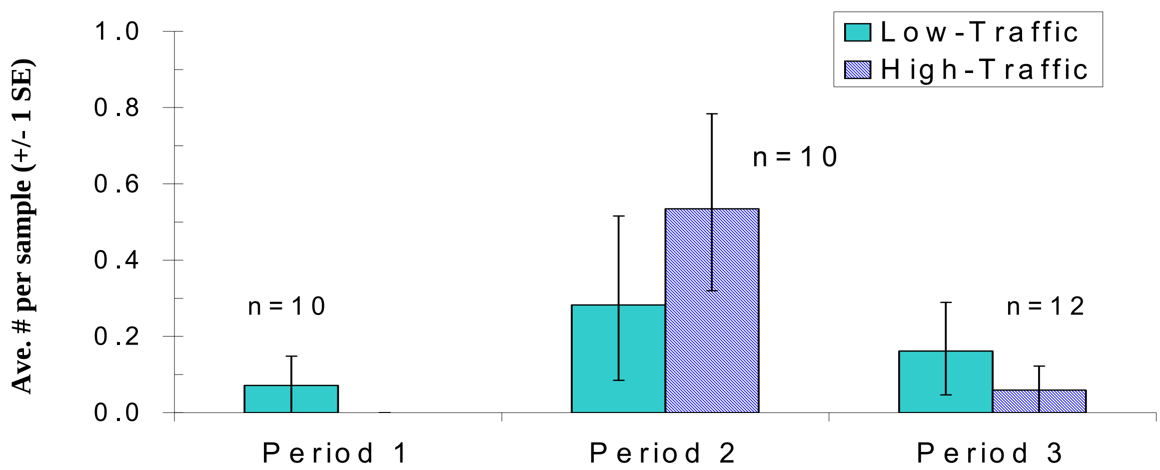


Figure 13

A. Sailor's Haven, pitfall traps



B. Cape Cod, wrack/core samples

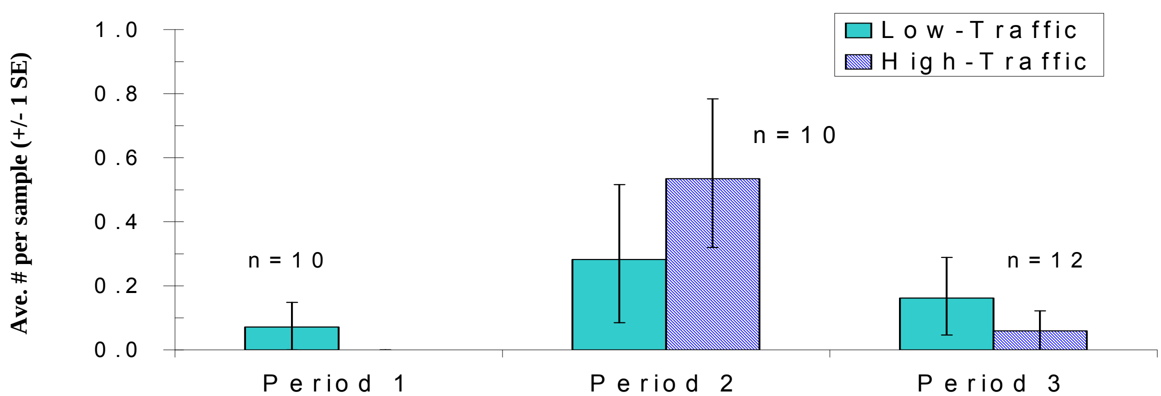
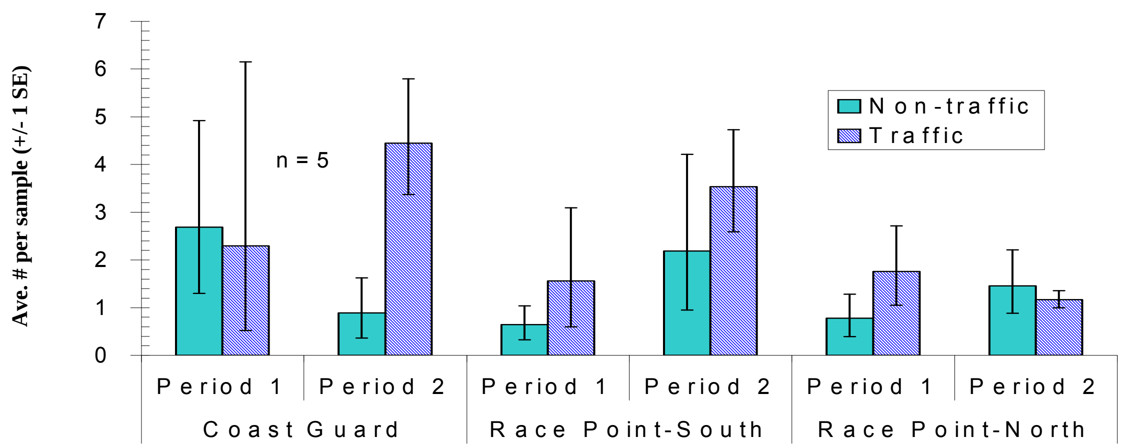


Figure 14

A. Cape Cod, 2001



B. Cape Cod, 2002

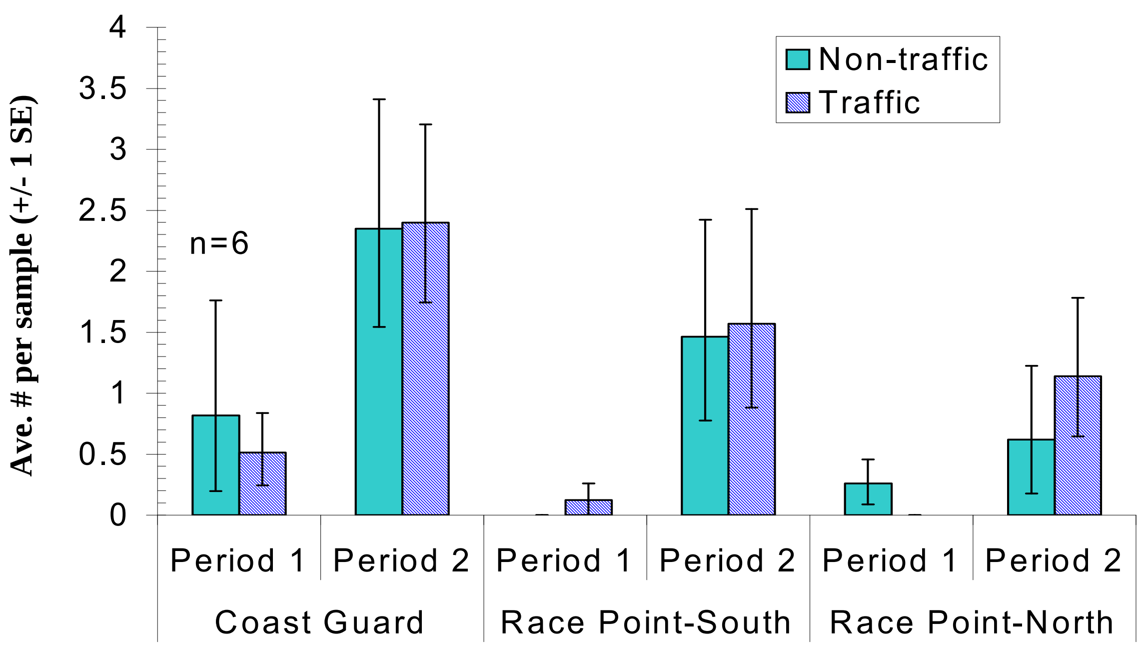
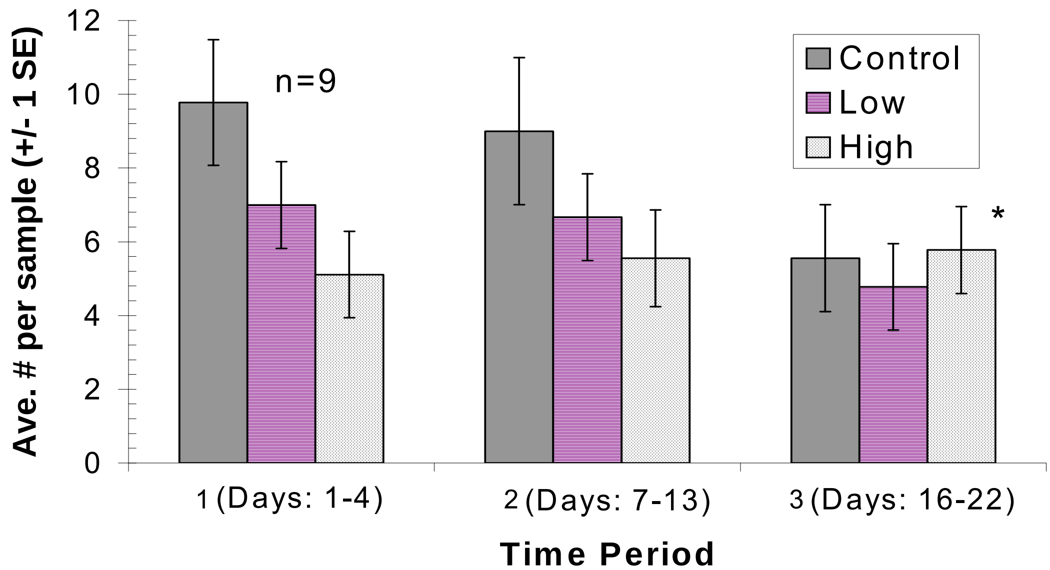


Figure 15

A. Overall abundance



B. *Phaleria testacea* larvae