Monitoring beach impacts: a case for ghost crabs as ecological indicators?

*Thomas A. Schlacher _Serena Lucrezi**
Faculty of Science, Health & Education; University of the Sunshine Coast; Maroochydore DC, QLD 4558, Australia.
*: presenting author

Abstract

Sandy beaches are under pressure from expanding coastal populations, ribbon development in the costal strip and increasing recreational use of beaches. In Queensland and elsewhere beaches are the prime sites for human recreation and their ecosystems are being extensively modified by development and direct human use. Yet, the ecological consequences of this process, especially for urban and peri-urban beaches, are poorly understood and criteria to measure the ecological health of beaches are not developed. We therefore tested the applicability of ghost crabs (Genus *Ocypode*) as ecological indicators on beaches. Ghost crabs offer practical advantages in that they are abundant and widespread and densities can be estimated by counting burrow openings. Because the crabs are the apex predators on beaches, their responses should also be ecologically meaningful. Densities of ghost crabs declined in areas subjected to habitat modification (i.e. seawall replacing dunes) and continuous trampling, suggesting predictable biological responses to human stressors. Crab numbers did, however, also change in response to natural variations in wave and wind regimes. This would confound the detection of impacts from human causes unless careful spatial and temporal replication is built into monitoring programs.

1. Introduction

Sandy beaches dominate Queensland's coastline and are the type of shoreline most intensively used by humans. In fact, significant parts of many coastal economies rely on the ecosystem services provided by beaches, most notably their role as prime areas for recreation and tourism. Rapid coastal development is also often concentrated along sandy shorelines, and population growth in coastal regions is significantly higher than elsewhere. Thus, human uses of beaches are increasing sharply (Schlacher et al. 2006; Schlacher et al. 2007a).

Beach management is, by tradition, almost exclusively focused on maintaining and restoring sand budgets, giving scant consideration for ecological dimensions (Nordstrom 2000; Schlacher et al. 2008) - environmental monitoring of beaches is rare. A monitoring technique which uses ghost crabs as biological indicators to measure the effects of human disturbance on beaches has been applied on urban shores (Barros 2001; Neves and Bemvenuti 2006), and to assess the effects of 4WD vehicles on beach biota (Moss and McPhee 2006a;

Schlacher et al. 2007b); these studies generally show reduced population densities of crabs in disturbed areas.

Ghost crabs of the genus *Ocypode* are semi-terrestrial invertebrates commonly found on subtropical and tropical shores. They are relatively large animals, occupying the position of apex invertebrate predator on sandy beaches (Wolcott 1978). Ghost crabs switch between surface activities at night to a fossorial lifestyle inside their burrows during the day (Barrass 1963). The crabs construct deep and complex burrows which provide shelter against climatic extremes and predators, and serve as refuges during moulting and maternity (Chan et al. 2006). The top of these burrows breaches the sand surface as a clearly visible hole, and therefore counting burrow entrances is an efficient tool to measure densities of ghost crabs on beaches (Moss and McPhee 2006a).

If management interventions are to reduce ecological impacts on Queensland's beach ecosystems, the development and testing of biological indicators becomes important. A critical component in this process is to assess whether the technique of using burrow counts of ghost crabs is robust in detecting human impacts on sandy shores. To this end, this paper examines three questions with respect to using ghost crabs as biological indicators on urban beaches: 1) to which degree are population estimates of ghost crabs influenced by external environmental factors?, 2) are measured responses of ghost crabs in relation to human disturbance consistent across space and time, and 3) does short-term human trampling bias estimates of population sizes derived from burrow counts?

2. Material and Methods

2.1. Study beach

The study was done on Mooloolaba Beach in SE Queensland, Australia (Figure 1). The beach has a long history of human engineering interventions and has undergone many morphological changes over the last 60 years (Longhurst 1997). A wooden retaining wall was built in 1952 on the northern backshore area of the beach and replaced by a stone wall in 1959; this structure was the forerunner of today's seawall which is 204 m long and 2.3 m high; this part of the beach also receives the highest number of beach visitors. All natural dune areas of the northern beach have been replaced with recreation infrastructures such as playgrounds, toilets and large buildings such as the Surf Life Saving Clubhouse. Dunes (3-4 m tall) are still present on the southern beach, although they have undergone substantial human difference such as fencing and re-vegetation since 1957 (Longhurst 1997).

Figure 1 Study area, Mooloolaba Beach, in Eastern Australia (a). The urban beach has a heavily modified and armoured section that is extensively impacted by human trampling (b), abutted by some remaining natural dune areas with relatively less human use (c). Burrow counts of ghost crabs were made in 3 × 10 m plots arranged sequentially (A–H) in across-shore transects from the base of the seawall or dune to the seaward limit of ghost-crab distributions. Each section (i.e. impact, reference) contained eight transects, surveyed on 15 separate occasions (photos by TA Schlacher (a), S Lucrezi (b, c))

2.2. Field measurements 1: impact of shore armouring on ghost crab abundance

To test whether ghost crab densities are reduced by shore armouring and intense human trampling, we compared burrow densities between the heavily modified northernmost section of the beach (impact section) and a reference zone 40 m to the south-east which is the area of the beach with the fewest number of visitors and where remnant dune vegetation remains (reference section). In each section (i.e. impact and reference), burrow counts were made across eight belt transects. Each belt transect was a continuous 10m wide strip that extended across the shore from the base of the foredunes or seawall to the downshore limit of burrow occurrence. Each transect was divided into sequential 3m long quadrats placed continuously down the shore. Thus, the basic sampling units in this study were 3 x 10m quadrats, and burrow densities are expressed as the number of burrows per 30 m^{-2}. Individual transects within each section were interspersed by 10 m along the beach. Burrow counts were temporally replicated on 15 days, covering a lunar cycle between March and April 2007. On each survey day, we started burrow counts 1-2 hours after sunrise; a complete survey of all transects taking 2-3 hours (the surveyors divided in two teams, one working on each section of the beach).

After all burrows had been counted in a quadrat, we took three replicate measurements of a) sand temperature to a depth of 5 cm (electronic thermometer Fluke 52 K/J), b) sand moisture to a depth of 8 cm (Trident microwave moisture meter), c) sand shear force resistance (field inspection vane tester Geonor H-60 with a vane size of 5 cm x 2.5 cm), and d) penetration force (Geotester penetrometer, 20 mm diameter tip); the position of replicates was randomised within each quadrat. We also recorded wind speed and air temperature (Skymate SM-18 meter), wind direction (compass), wave height (visually) and wave period (counts of breaking waves over 3 min) at the start and end of each survey. Additional weather data (e.g. hourly temperature, wind speed and direction, hourly rainfall) and tidal heights were obtained from the Bureau of Meteorology (www.bom.gov.au). Estimates of the number of beach visitors were obtained from life guards who patrol the beach daily from 7:30 to 16:30, and count the number of people every two hours.

2.3. Field measurements 2: short-term trampling bias

The response of burrow density and size to foot traffic was tested in a series of experiments where human trampling was repeatedly applied to ghost crab burrows on the beach. Experiments were conducted in four experimental plots (5 x 3 m) established in the upper intertidal zone near the drift line. Plots were fenced to exclude interference from the public. Human trampling was applied to two plots and the remaining plots served as controls (i.e. human exclusion, no trampling). To prevent physically disturbing the control plots - and the impact plots before the experimental application of trampling impacts began – we used a scaffold. It consisted of a ladder lifted 30 cm above the ground by trestles placed outside the boundaries of the experimental plots. Field operators moved systematically across the ladder and measured the burrow openings below through the spaces between the rungs.

The experiments were run over four consecutive days. On each occasion, we counted all burrows and measured their sizes (diameter to the nearest mm using a ruler) in each plot at 07:00 (ca. 2 h after sunrise) before any disturbance was applied. The trampling treatment consisted of two people (weight: 45 & 55 kg) crossing the impact plots each 50 times in a zig-zag pattern; this resulted in close to 100% coverage of footprints. The trampling treatment was applied in 5 distinct bouts at 50 min intervals over a 5 h period. Before each new trampling event, all burrows which remained intact were counted and their diameter measured.

3. Results

3.1. Environmental influence on changes in ghost crab numbers

Significantly higher burrow counts were obtained in wetter sand after warm nights and during stronger winds (Table 1). By contrast, wave properties, tidal amplitudes, sand temperature and compactness were not correlated with the number of burrow openings (Table 1). No substantial difference in sediment properties occurred between sections of the beach (Table 1). Correlations between environmental variables and burrow densities were not influenced by human disturbance intensity, and variation in environmental variables was unlikely to be the primary cause of spatial differences in ghost crab populations between sections of the beach. There was no conspicuous pattern in temporal changes of burrow numbers that could unambiguously be related to lunar phases.

3.2. Habitat disturbance vs. changes in burrow densities

Burrow densities were substantially lower in areas intensively trampled by humans and where dunes had been replaced by a seawall (Figure 2). Overall, the highly impacted site supported only half the number of crabs found in the less intensively disturbed areas. These spatial contrasts between heavily and less disturbed sites were, however, not necessarily consistent over time (Table 2). On the upper shore, half the surveys showed significantly lower mean densities in the impacted site, and the direction of change was negative for all but a single survey (Table 2). By contrast, although burrow densities on the middle part of the beach (i.e. below the strandline) were also mostly lower in the heavily impacted areas, a significant change could only be detected in a single survey (Table 2).

3.3. Trampling impacts on crab burrows

Pedestrian traffic substantially reduced burrow densities and sizes immediately after the trampling impacts had occurred; it did, however, not cause significant changes at a time scale of days. Mean burrow densities were reduced by 88% following human trampling impacts (Figure 3). In all experiments, densities in impact plots (0.36 ± 0.03 burrows m ^{2}) were significantly lower than in un- trampled reference plots (2.85 ± 0.13 burrows m ^{2}; Fig. 2; ANOVA - effect treatment: $F_{(1,7)} = 83.72$, $P < 0.001$). The first set of impacts (i.e. 100 passes) caused the greatest change to the density of ghost crab burrows; further trampling had comparatively small additional effects (Figure 4). There was no significant interaction between treatment and experiment (ANOVA – experiment x treatment, $F_{(3,7)} = 1.23$, $P = 0.37$), suggesting that experimentally produced effects of trampling on burrow counts were consistent across all experiments.

Because experiments were run on consecutive days and the sets of trampling impacts were separated by at least 19 hrs between experiments, changes to the density and size of crab burrows which were measured at the start of each experiment should be indicative of short-term (i.e. days) impacts on ghost crab populations. However, we neither found a significant difference in burrow numbers nor burrow sizes between the impact and control plots before trampling commenced in each experimental run. This lack of significant day-to-day changes, which could not be linked to the intensity of human disturbance, suggests that crabs of all sizes repaired their burrows overnight, resulting in densities and size structures that were indistinguishable from pre-impact conditions in the short term.

4. Discussion

4.1. Environmental influence on changes in ghost crab numbers

We found a strong positive correlation between wind speed and burrow density (Table 1). Fewer people frequent the beach when there are strong onshore winds. Also, wind-driven onshore advection is the main mechanism for delivering wrack and carrion to beaches. This is likely to explain the higher activity of ghost crabs during strong onshore winds.

Although ghost crabs can occupy a fairly broad area across the intertidal and supratidal gradient, the distribution of many species appears to be centered on the backshore, extending from the driftline to the dune. Ghost crab distribution may also shift in relation to tides. In the present study, wave properties and tidal amplitudes were amongst the environmental variables that did not affect the number of ghost crab burrow openings. However, the surveys were carried out over one month only, providing limited tidal ranges.

Further studies may look at prolonging the time of sampling, in order to include phenomena such as king tides, which are possibly likely to have a substantial influence on the density and distribution of ghost crabs on the beach.

4.2. Trampling impacts on crab burrows

Significant decreases in burrow counts denote a negative effect on ghost crab populations, but the actual mechanisms that cause these declines remain unknown, except for the impact of off-road vehicles that can directly crush crabs (Wolcott and Wolcott 1984; Schlacher et al. 2007b). Putative causes of population declines in ghost crabs span a wide ambit such as: (a) direct crushing of crabs through trampling (but see our short-term trampling experiments), (b) habitat loss and/or modifications; (c) changes to metabolic costs, reproduction, and behavior, (d) trophic shifts and enhanced predation pressures, and (e) light pollution.

Intense, human trampling did result in lower burrow count but the effects of the short-term trampling disturbances were mostly non-lethal to ghost crabs and did not last long. A single hit by a pedestrian suffices to cover or collapse a burrow opening, and because the crabs do not to re-open filled burrow entrances for at least one hour (S. Lucrezi, personal observation), burrow counts fell markedly after people had walked over the plots (Figure 3). Burrow numbers recovered, however, overnight, showing that human trampling is not necessarily lethal to most crabs. In the long-term, human trampling does, however, have demonstrable, negative impacts on ghost crab population sizes (Figure 2), most likely as a consequence of several, additive sublethal effects related to frequent habitat disturbance. Also, other short-term trampling experiments have demonstrated direct mortalities of macrobenthic species on sandy beaches (Moffet et al. 1998).

It has been suggested that ghost crabs can acclimatize to increasing levels of recreational beach use (Steiner and Leatherman 1981). Even positive effects of recreation have been reported when food scraps left by beach visitors provide a trophic subsidy to the scavenging crabs (Steiner and Leatherman 1981). Yet, on many beaches pedestrian trampling is a heavy and continuous disturbance agent that causes significant negative impacts on ghost crab populations in the long term (Figure 2)

We found a positive correlation between wind speed and burrow density (Table 1). Fewer people frequent the beach when there are strong onshore winds (S. Lucrezi, personal observation), reducing direct trampling impacts by humans. Ghost crabs can be highly active during strong onshore winds (Wolcott 1978), and onshore winds deliver wrack and carrion to beaches. We observed nocturnal feeding aggregations of ghost crabs around driftlines (TA Schlacher pers. obs.), and ghost crabs may therefore become more active when stronger winds increase the food supply of wrack. However, the positive relationship between wind speed and burrow numbers measured in this study will not apply over the full spectrum of wind speeds. In fact, winds above 20 knots tend to obscure burrow openings, particularly in loose sand on the upper shore (TA Schlacher pers. obs.). Thus, burrow counts are not useful as a monitoring tool during strong winds.

Coastal armouring has often been employed to combat shoreline erosion worldwide, and this trend may escalate in the face of global climate change (Feagin et al. 2005). The main ecological impact of coastal armouring is the destruction of dunes (Dugan and Hubbard 2006). Since dunes are critical refuges for ghost crabs during storms (Christoffers 1986), crabs on armoured sections of beaches are at greater risk during high seas (Vinagre et al. 2007).

Evidence for numerous ecological effects linked to beach recreation is accumulating (Davenport and Davenport 2006; Moss and McPhee 2006b), but ecological assessments of sandy beaches are rare (Schlacher et al. 2008). Neglect of ecological dimensions in beach management stems partly from the lack of established monitoring techniques using tested indicators for sandy shores. This paper shows that ghost crabs are useful in principle, but potential bias must be recognized and avoided.

A key requirement of all monitoring is to standardize data collections across geographic regions and programmes. Here we show that several environmental factors can significantly influence burrow numbers, including temperature, wind speed, and sand moisture. Therefore, future monitoring using ghost crab burrow counts should either limit field surveys to defined ranges of weather conditions, or explicitly incorporate environmental conditions in both the reporting and analysis.

Bias in burrow counts and sizes (Figures 2&3) has consequences for using ghost crabs as ecological indicators: both counts and opening diameters are only reliable proxies for population densities and size structures if field measurements are taken when pedestrian disturbance is small. Thus, field surveys should be limited to periods when beach visitors are expected to be few - as early in the morning as possible - on weekdays rather than weekends and public holidays, and during cooler and overcast conditions rather than during sunny weather. Provided such basic design factors are explicitly incorporated into standard operating procedures for field surveys, ghost crab burrow counts can be a rapid and cost-effective indicator to determine the extent of ecological disturbance from human uses of sandy beaches.

Take home messages

Mitigation measures and management interventions that seek to reduce negative ecological effects will invariably have to target the process causing the observed impacts. In the case of ghost crabs on urban beaches, it appears logical to propose human trampling as a prime mechanism of impact (but see Jaramillo et al. 1996). Robust scientific evidence to support the need for management interventions requires, however, that an unequivocal link between the level and nature of human disturbance and the biological response is demonstrated; this can only be achieved through controlled, and carefully designed manipulative experiments (Bulleri et al. 2007). Thus, a major lesson from this study is that the mechanistic links between putative human pressures and biological responses need to be determined (see also Schlacher et al. 2007b).

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Table 1 Partial correlations between environmental factors and densities of ghost crab burrow densities measured in 15 surveys on two sections of Mooloolaba Beach.

	Reference Section		**Impact Section**	
Sediment Properties				
Sand Temperature (°C)	-0.207	ns	0.003	ns
Sand Compactness (Kpa)	-0.340	ns	0.141	ns
Sand Moisture (%)	**0.561**	*	**0.714**	*
Sea Conditions & Tides				
Wave Height (m)	0.264	ns	0.160	ns
Wave Period (s)	-0.183	ns	0.003	ns
Tidal Amplitude (m)	-0.107	ns	-0.220	ns
Tidal Reach (previous night; m)	0.080	ns	0.079	ns
Tidal Reach (survey day; m)	-0.065	ns	-0.145	ns
Weather				
Air Temperature - Night (18:00-06:00; °C)	**0.603**	*	**0.717**	*
Air Temperature Day (06:00-12:30; °C)	-0.403	ns	-0.432	ns
Wind Speed - Night (knots)	**0.666**	*	**0.681**	*
Wind Speed - Day (knots)	**0.585**	*	**0.597**	*
Human Pressure				
Beach Visitors (daily, n)	-0.326	ns	-0.342	ns

Table 2 Effect sizes for spatial contrasts in the density of ghost crab burrows between impact and reference sections during 15 surveys at Mooloolaba Beach. Negative values signify lower densities at impacted sites, whereas positive values denote higher densities in the disturbed areas. Bold entries denote significant differences between means.

	Upper Shore			**Middle Shore**		
Survey	**Effect Size [#]**		**P [$]**	**Effect Size [#]**		**P [$]**
1	**-21.4**	**(-59%)**	*	12.1	(+35%)	ns
2	**-25.1**	**(-63%)**	***	-25.0	(-43%)	ns
3	-10.8	(-47%)	ns	-6.4	(-19%)	ns
4	**-15.0**	**(-71%)**	**	-0.3	(-1%)	ns
5	-20.6	(-65%)	*	-5.0	(-13%)	ns
6	**-22.2**	**(-89%)**	***	-13.0	(-33%)	ns
7	5.3	(+61%)	ns	-15.0	(-38%)	ns
8	**-15.5**	**(-95%)**	***	**-27.6**	**(-87%)**	*
9	-9.9	(-46%)	ns	-0.3	(-1%)	ns
10	-3.3	(-60%)	ns	3.0	(+32%)	ns
11	**-13.8**	**(-52%)**	**	-2.3	(-7%)	ns
12	**-8.4**	**(-95%)**	**	-24.2	(-85%)	ns
13	-9.5	(-66%)	ns	7.5	(+55%)	ns
14	-8.5	(-60%)	ns	-14.4	(-47%)	ns

No. Negative Contrasts	13		11	
No. Positive Contrasts	1		3	
	Z-statistics	P	Z-statistics	P
Sign-Test	3.10	0.002	1.87	0.061

[#] Effect Size = ($-\text{Density}_{\text{Impact}}$ - $-\text{Density}_{\text{Reference}}$);

[$] Probability values from HSD post-hoc tests following significant time x zone x impact effects in the main GLM model. *** P < 0.001, ** P < 0.01, * P < 0.05, ^{ns} P > 0.05.

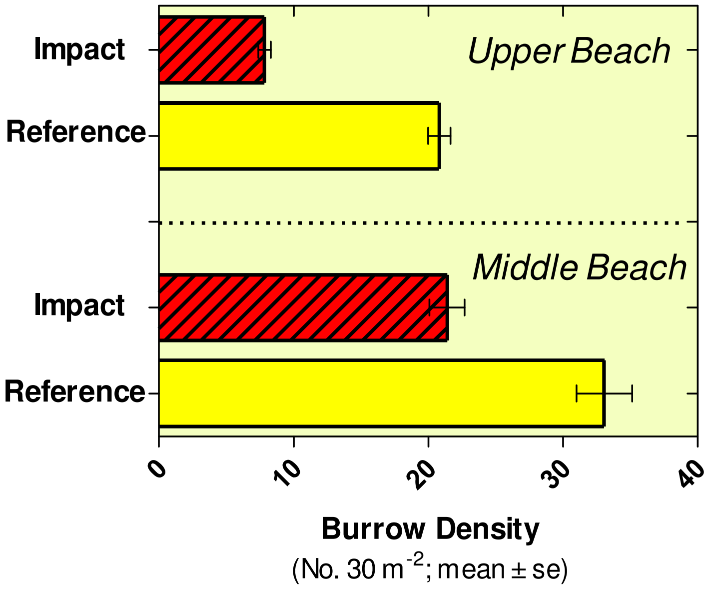

Figure 2 Contrast in the density of ghost crab burrow openings between a beach section armoured with a seawall and heavily trampled (“impact”) compared with a beach section with some remaining dunes and less impacted by pedestrians (“reference”) at Mooloolaba, SE-Queensland.

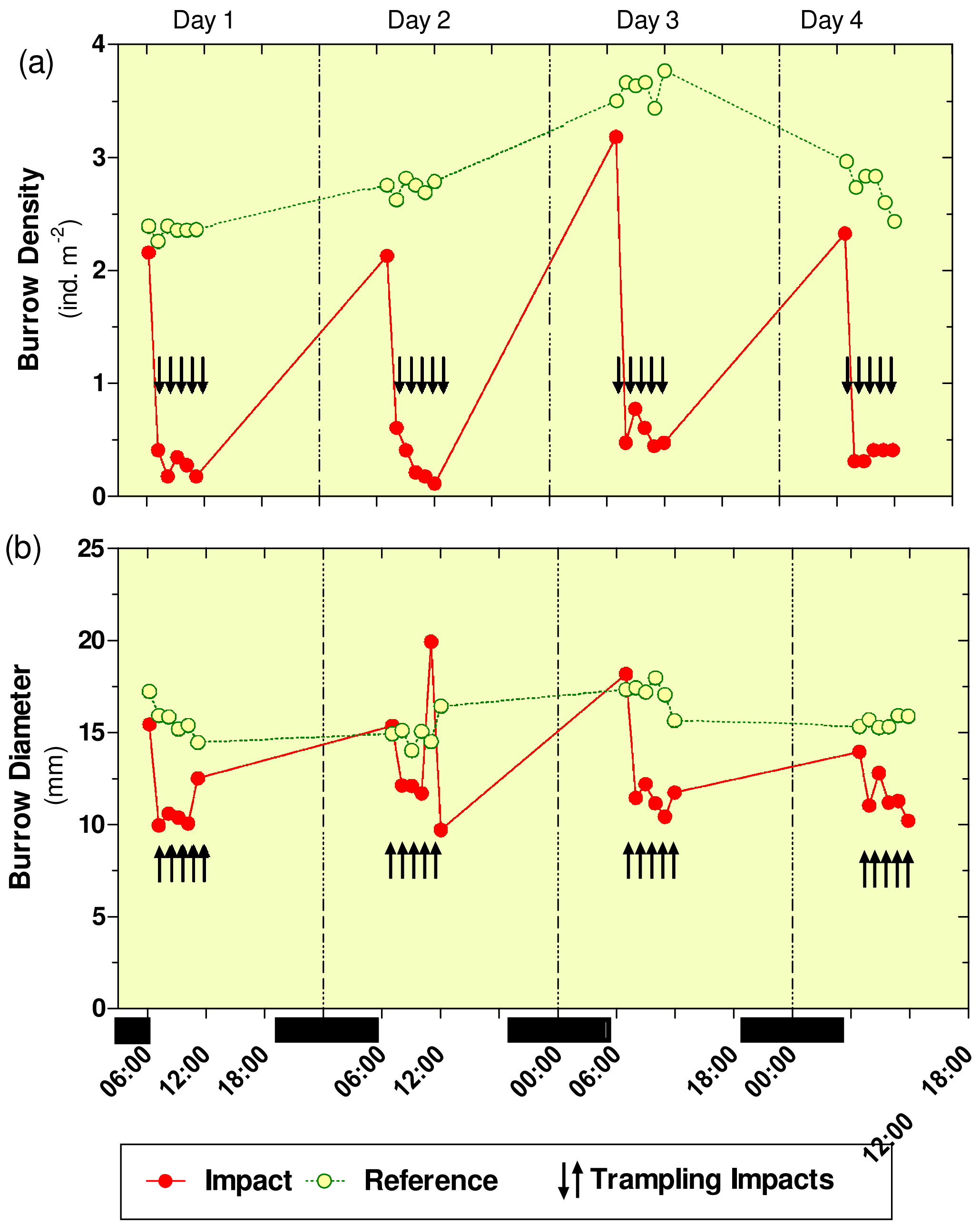

Figure 3 Variation in mean burrow counts (a) and burrow size (b) of ghost crabs in relation to experimental disturbance by human trampling. Experimental treatments consisted of 100 pedestrian passes applied five times at 50 min intervals in four separate experimental runs (days) compared with abutting control sites from which beach visitors had been excluded.

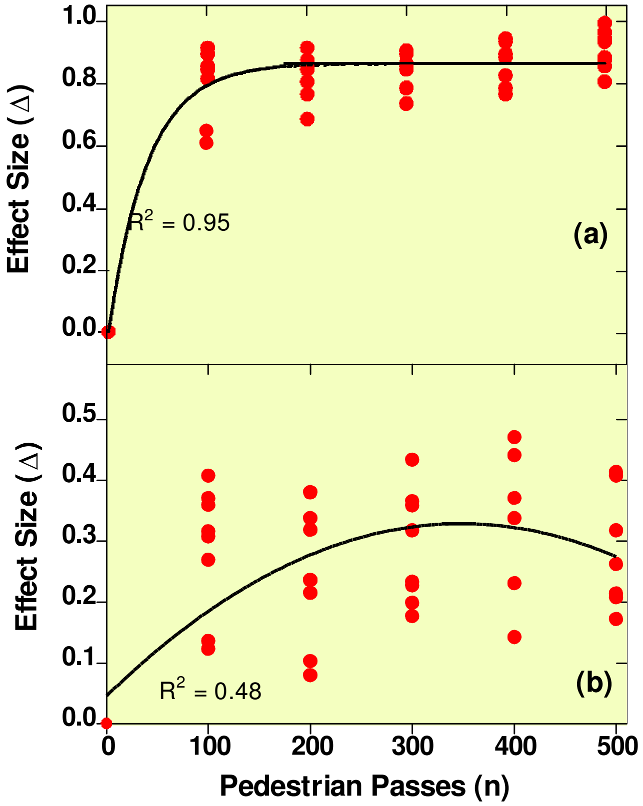

Figure 4

Relationship between changes in ghost crab burrow numbers (a) and opening diameter (b) in relation to the intensity of human disturbance through pedestrian trampling. Effect size (Δ) is measured as: |($_{Ref.}$ – $_{Imp.}$) / $_{Ref.}$ |, where are the mean values of burrow density or entrance diameter in the reference (Ref.) and impact (Imp.) treatments.