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The Recovery of Crustacean Populations in Lamlash Bay No-Take Zone, Scotland

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Abstract

Marine protected areas can safeguard against overfishing, promote increased resilience and productivity within their boundaries and offer the opportunity for enhanced fisheries landings in surrounding waters. This study investigates the response of commercially valuable crustacean populations to protection in a temperate marine protected area (MPA) – Lamlash Bay no-take zone (NTZ). Data was collected within the NTZ and a near and far control zone through fishing surveys and passive fishing observations aboard commercial creeling vessels during July and August 2013. Data gathered included the abundance, size and gender of European lobster, brown crab and velvet crab and the prevalence of disease and injury in lobster. A tag and release program was undertaken to assess growth rates and movement patterns in the NTZ and surrounding waters. Lobster showed a strong response to protection, being 33.8% more abundant and 8.52% larger compared to the Near Control, with legal-sized lobster 118.5% more abundant. Conversely, crab was significantly less abundant in the NTZ, with highest abundance in the Control locations. Relationships of catch per unit effort (CPUE) and mean size of lobster *vs.* distance from the NTZ boundary show a significant negative trend, with elevated CPUE within 350m of the NTZ indicating that spillover may be occurring. No significant difference was evident in the rate of disease or injury in the NTZ compared to the Near Control, suggesting that the lobster population remains healthy despite increases in abundance. Over the preceding 12-month period total lobster abundance in the NTZ increased by 12.34%, legal lobster abundance increased by 20.86% and mean size increased by 1.56%. Conversely, total abundance and legal abundance in the Near Control fell by 3.89% and 5.86%, respectively, while mean size remained constant.

Introduction

Rapid intensification in fishing effort over the course of the 20th century has led to the degradation of marine ecosystems on a global scale (Jackson, 2008; Srinivasan et al., 2012). Past studies have highlighted an array of impacts, including a loss of biodiversity (Coll et al., 2008) trophic cascades (Daskalov et al., 2007) and reduced ecosystem resilience (Ling et al., 2009). Consequently, fishing has become the most studied anthropogenic disturbance within the marine environment (Myers and Worm, 2003). In an attempt to conserve biodiversity and promote habitat recovery, the designation of marine protected areas (MPAs) is often suggested – a management tool that is attaining an increasing level of scientific endorsement over recent years (Halpern et al., 2010; Moland et al., 2013). Numerous approaches exist under the umbrella of MPAs, which vary in the level of protection offered, and therefore, ultimately, in the benefits derived (Sciberras et al., 2013). At the top end of this spectrum are no-take zones (NTZs), within which the extraction of all resources is prohibited (National Research Council, 2001). NTZs can foster greater abundances of species and larger, more fecund individuals within their boundaries (Walters et al., 2007). Furthermore, there is potential for this increase in production to 'spill over' into surrounding areas, thereby contributing to increases in fisheries landings in adjacent waters (Gell and Roberts, 2003; Goni et al., 2010; Russ and Alcala, 2011).

This study focuses on the response of three commercially valuable crustacean species – European lobster, *Homarus gammarus*, brown crab, *Cancer pagurus*, and velvet crab, *Necora puber*, to protection in a temperate NTZ. Landings of the three species generate over £31 million annually in Scotland - £13.3 million from brown crab, £11.7 million from lobster and £6.4 million from velvet crab (Marine Scotland, 2012). In the UK as a whole over £70 million is generated annually (Marine Management Organisation, 2012). Together they comprise a quarter of UK shellfish landings by value and hence represent a considerable economic interest. However, despite their value, all three species display signs of an overexploited stock, with assessment from Marine Scotland (2012) indicating that within the Firth of Clyde exploitation is above the point at which long-term sustainable

exploitation (F_{max}) can be achieved (Figure 1).

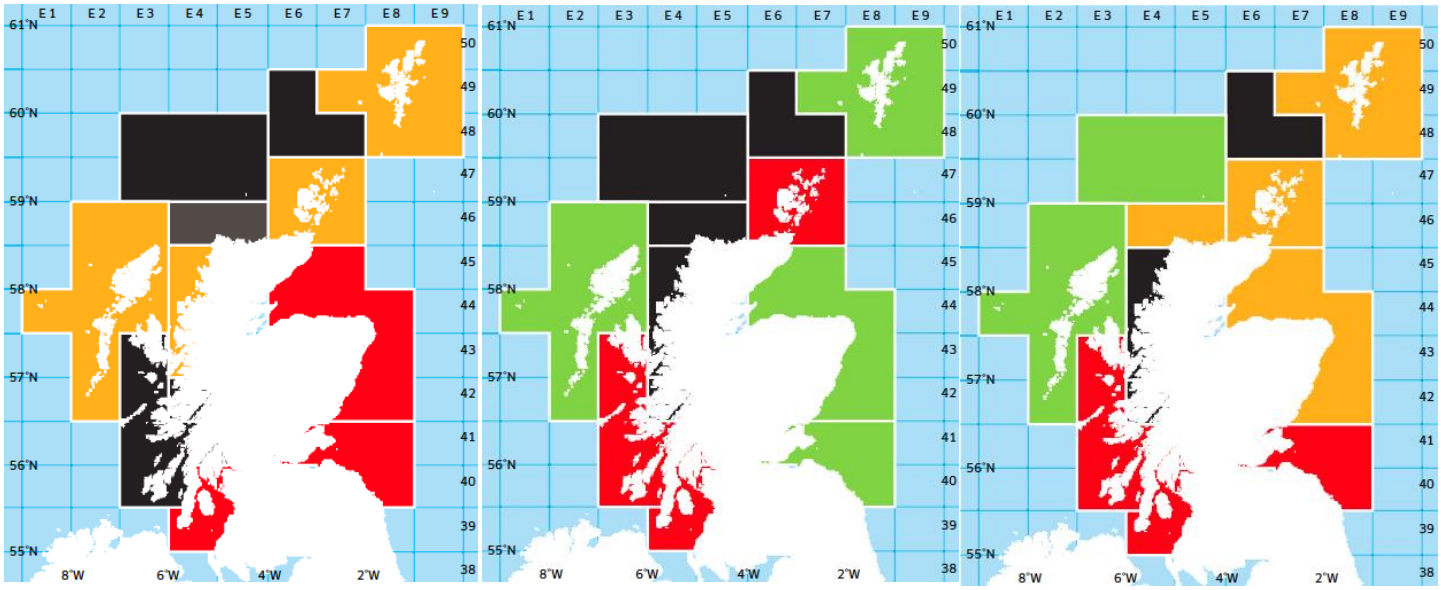


Figure 1. Marine Scotland stock assessments for lobster (*left*), velvet crab (*centre*) and brown crab (*right*) based on creel fishery mortality from 2006-2010. The Firth of Clyde (bottom left coloured segment) indicates fishing mortality significantly above F_{max}, represented by the red shading. Adapted from Marine Scotland (2012).

Collapse of these stocks could therefore induce considerable economic loss, while Boudreau et al. (2012) also demonstrated the ecological value of large benthic decapods, with many species playing an important structuring or keystone role in ecosystems through suppression of other species. There is therefore significant importance in implementing effective conservation measures to achieve sustainable exploitation of these species.

Past studies have shown relatively confined migration patterns in both brown crab and lobster. Agnalt et al. (2007) undertook a lobster tag and release program, with 95% of recaptures occurring within <1km of the release point, while Oresland and Ulmestrand (2013) found that 98.6% of tagged lobsters had moved <1km upon recapture. Similarly, ultrasonic tracking methods employed by Moland et al. (2011) showed maximum movement of 379m during a median observation period of 315 days. Although brown crab is known to undertake longer migrations, mark and release studies by Ungfors et al. (2007) demonstrated mean movement of 4.4km and 11.2km for male and female brown crab,

respectively, with the majority of recaptures occurring within a one-year period. Consequently, these species represent ideal candidates for protection under a network of inshore MPAs, which, if correctly implemented and enforced, should aid in population recovery. Comparatively less is known about the movement patterns of velvet crab, with no tagging studies conducted, likely due to their lower economic value and considerably smaller body size, which complicates tagging techniques. Regardless, for an MPA to offer tangible and relevant benefits in the long term, monitoring and assessment is crucial (Withy-Allen and Hovel, 2013). Through this process it is possible to evaluate the effectiveness of reserves against a set of pre-determined goals, and alter approaches where necessary.

Prior to the designation of the NTZ in 2008, the area was commercially fished for all three target species (C. Weir, pers. comms., 2012), suggesting that populations of these species may benefit through protection from fishing. Indeed, past studies have highlighted the effectiveness that MPAs can play in restoring both crab and lobster populations elsewhere. Hoskin et al. (2011) found lobster to be 500% more abundant and 9% larger compared to surrounding areas in Lundy NTZ, England. Follesca (2007) found the mean abundance of spiny lobsters, *Palinurus elephas,* to be ~750% more abundant within a Mediterranean marine reserve, and Wootton et al. (2012) found lobster to be ~800% more abundant in Lundy Island NTZ relative to a nearby control site. However, despite these positives, Wootton et al. (2012) demonstrated higher levels of disease and physical damage at Lundy Island, attributed to the higher densities of lobster within the reserve, suggesting that there may be adverse effects that need to be considered when designating and managing protected areas.

This study therefore seeks to establish whether crab and lobster populations have benefitted from the protection afforded by Lamlash Bay NTZ, with the following aims:

1) Compare abundance of crab and lobster between the NTZ and a Near Control zone

2) Compare abundance of crab and lobster between the NTZ and a Far Control Zone

3) Compare the mean size of crab and lobster between the NTZ and the Near Control zone

4) Investigate the prevalence and severity of physical damage and disease of lobster populations in the NTZ compared to the Near Control zone

Methods

- Study site

Lamlash Bay lies on the eastern coast of the Isle of Arran, in the Firth of Clyde, Scotland. It measures approximately 4.5km by 2.5km, receiving significant shelter through the presence of Holy Island to the east (Figure 2). Within the bay and surrounding waters, commercial fisheries exist for European lobster, brown crab, king scallops, *Pecten maximus,* and langoustine, *Nephrops norvegicus*, while a seasonal fishery also exists for velvet crab. On 20th September 2008 the north eastern extent of the bay was designated as an NTZ (Figure 2) through creation of the Inshore Fishing (Prohibition on Fishing) Order, 2008, designated under the Inshore Fishing (Scotland) Act, 1984. The NTZ encompasses 2.67 km^2 of the bay (Thurstan and Roberts, 2010) and covers a diverse range of habitats, including maerl beds and areas of muddy, rocky and sandy sediment, with lobster and crab habitat existing in the southern area of the NTZ and a small area to the northeast.

The abundance and size distribution of crab and lobster was measured within the NTZ, in addition to two control sites. The Near Controls (N1-N3; Figure 2) were in close proximity to the NTZ (<2.5km), primarily around the eastern and western coast of Holy Island, while the Far Controls (F1-F3; Figure 2) were more distant, located approximately 10-20km from the NTZ on the south eastern and southern coast of Arran. All control sites covered a similar area of lobster habitat to that which exists inside the NTZ, ran parallel to the shoreline and were actively fished by similar intensities of both commercial and recreational creelers at the time of sampling.

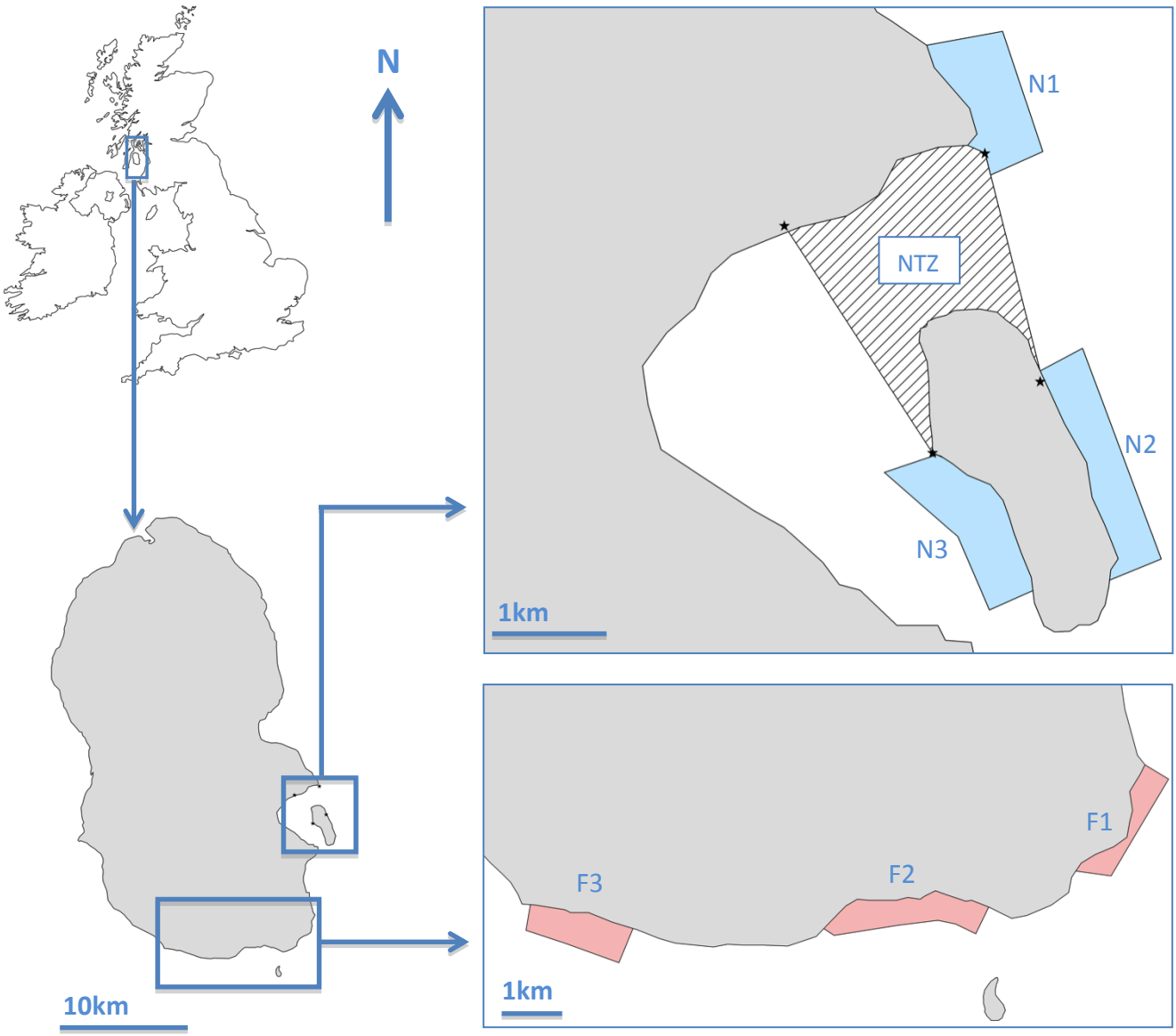


Figure 2. The location of the Isle of Arran within the UK, showing the position of the near controls (N1-3) and far controls (F1-3) in relation to the NTZ (hashed).

- Data collection

Data were collected through a combination of passive fishing observations and sampling surveys aboard a 9.35m commercial fishing vessel – the Kimberley OB345, with further fishing observations in close proximity to the NTZ made aboard a smaller commercial vessel – the Julie Anne TT268. Both approaches used parlour creels - baited with whole salted herring throughout, excluding one survey period where a combination of salted herring and fresh gurnard was used. Each creel measured approximately 64 x 38 x 41cm, with 2 entrances that each measured 21 x 18cm, deployed in strings of differing lengths. During passive observations the majority consisted of 10 creels, while strings used

during the sampling surveys all consisted of 5 creels. Consequently, CPUE measurements were based upon the average number of each species caught per individual creel – thereby negating the impact of varying string lengths. During both methods a length of 10 fathoms (18.288m) was present between each creel on a string. This relatively low distance meant there was potential for creels to impact the catch rate of neighbouring creels on the same string (Smith and Tremblay, 2003). Hence, each string, as opposed to each creel, was treated as a single control. Sampling surveys were conducted during two one-week periods, once each in July and August 2013, with strings deployed evenly within the NTZ and in adjacent waters outside the NTZ. Each string was soaked for 48 hours prior to retrieval during sampling surveys, while measurements taken from creels during passive observation were soaked for 48-72 hours. While this has the potential to inflate measures of abundance, Montgomery (2005) showed that soak times of 24-72 hours had no significant difference on the overall catch rates of lobster.

- *Variables recorded*

The abundance of each target species and any bycatch species caught per pot during the sampling surveys were recorded, with individuals sexed and measured to the nearest millimetre using

Figure 3. Examples of the criteria used to assess the health of lobster in the NTZ and Near Control during the August 2013 surveys. Damage includes loss and new regrowth of antennae *(top, left)*, shell disease *(top, right),* physical injury to exoskeleton *(bottom, left)* and loss/regrowth of claw *(bottom, right).*

vernier callipers. Measurements for lobsters consisted of the carapace length (CL), measured from behind the eyestalk to the posterior edge of the carapace where the connection with the abdomen is formed, while crabs were measured at the widest point of the carapace. During passive fishing observations, the number of velvet crab and juvenile brown crab and lobster (<140mm carapace width and <87mm carapace length, respectively) were recorded, while all crabs and lobster above minimum landing size were measured, sexed and the absence of claws or berried females was noted. The same observations were made during the July sampling surveys, whereas during the August sampling surveys more detailed observations were made on the presence of shell injury and disease (Figure 3). Following inspection, photos were taken of each individual injury to allow for more accurate identification at a later date.

- Tagging

All lobster and a proportion of brown crab were fitted with a T-bar anchor tag (Hallprint Pty. Ltd, South Australia), chosen due to the quick application and high rate of retention during the moulting phase (González-Vicente et al., 2012). Each tag was individually numbered and coloured green to denote individuals captured inside the NTZ, or red to denote those captured outside the NTZ. All tags contained University of York contact details and measured 55mm total length, 40mm filament length. Tags were inserted using a Monarch Marking 3030 tagging gun and anchored into the muscle of both species. Lobsters were tagged in the abdominal muscle immediately behind the posterior edge of the carapace, either side of the midline to avoid puncturing the dorsal abdominal artery or gut, while crabs were tagged in the posterior opening between the hind legs and carapace. Once tagged, all individuals were promptly returned to the sea in the location they were caught.

- Statistical methods and data analysis

Statistical analysis was performed in R (version 3.0.0), with spatial analysis performed in ArcGIS (version 10.1). The distance of each string from the NTZ was calculated based upon absolute minimum distance. In situations where land was present between the string location and the NTZ, distance was calculated based upon the shortest distance along the coastline.

Due to the relatively low sample size, data collected during sampling surveys in the Near Control was combined with that obtained through passive fishing observations within the same geographic areas, while data in the Far Control zones consisted entirely of passive fishing observations. Data within each of the locations (N1-3 and F1-3) were then pooled to provide an overall dataset covering both the Near Control and Far Control zones.

Unpaired T-tests were used to assess differences in CPUE and mean size for each of the three target species between the NTZ and Near/Far Control and between the Near Control and Far Control. Kolmogorov-Smirnov tests were conducted prior to analysis to confirm that data followed a Gaussian distribution, while Levene's tests were conducted on the variables in each zone to confirm that homogeneity of variance was present (Gastwirth et al., 2009). Due to the relatively small sample size,

Fisher's exact tests were used to assess differences in gender and physical characteristics, including the prevalence of berried females and levels of injury and damage between the NTZ and Near Control (Wong, 2011). All tests were two-tailed with a significance level of $\alpha>0.05$. Finally, Spearman's rank correlation tests were used to investigate the relationship between catch rates and mean lobster size *vs.* distance from the NTZ.

Results

- Crustacean abundance (aim 1 & 2)

- Lobster

Total CPUE of lobster was 33.8% higher inside the NTZ compared to the Near Control (Table 1; unpaired T-test, p=0.0027; Figure 4a and Table A1) and 38.8% higher compared to the Far Control (Table 1, unpaired T-test, p=0.0001; Figure 4a and Table A2). The NTZ harboured considerably higher abundances of larger sized individuals (Figure 5). Legal sized lobsters (>87mm CL) were 118.5% more abundant in the NTZ compared to the Near Control (Table 1; unpaired T-test, p<0.0001; Figure 4b and Table A1) and 167.94% more abundant compared to the Far Control (Table 1; unpaired T-test, p<0.0001; Figure 4b and Table A2).

Absolute mean lobster CPUE inside the NTZ increased by 55.94% between August 2012 and August 2013 (from 1.06 to 1.653), while CPUE of legal-size lobster increased 72.66% over the period (0.64 to 1.105). However, six of the 20 strings deployed in 2012 were located on muddy sediment, a habitat where lobster are known to be scarce. Therefore, comparing only surveys performed upon known lobster habitat yields increases of 12.34% in total CPUE (1.471 to 1.653) and 20.86% in legal CPUE (0.914 to 1.105). Conversely, lobster abundance in the Near Control decreased by 3.89% over the same period (1.288 to 1.235), while legal CPUE decreased by 5.86% (0.538 to 0.506).

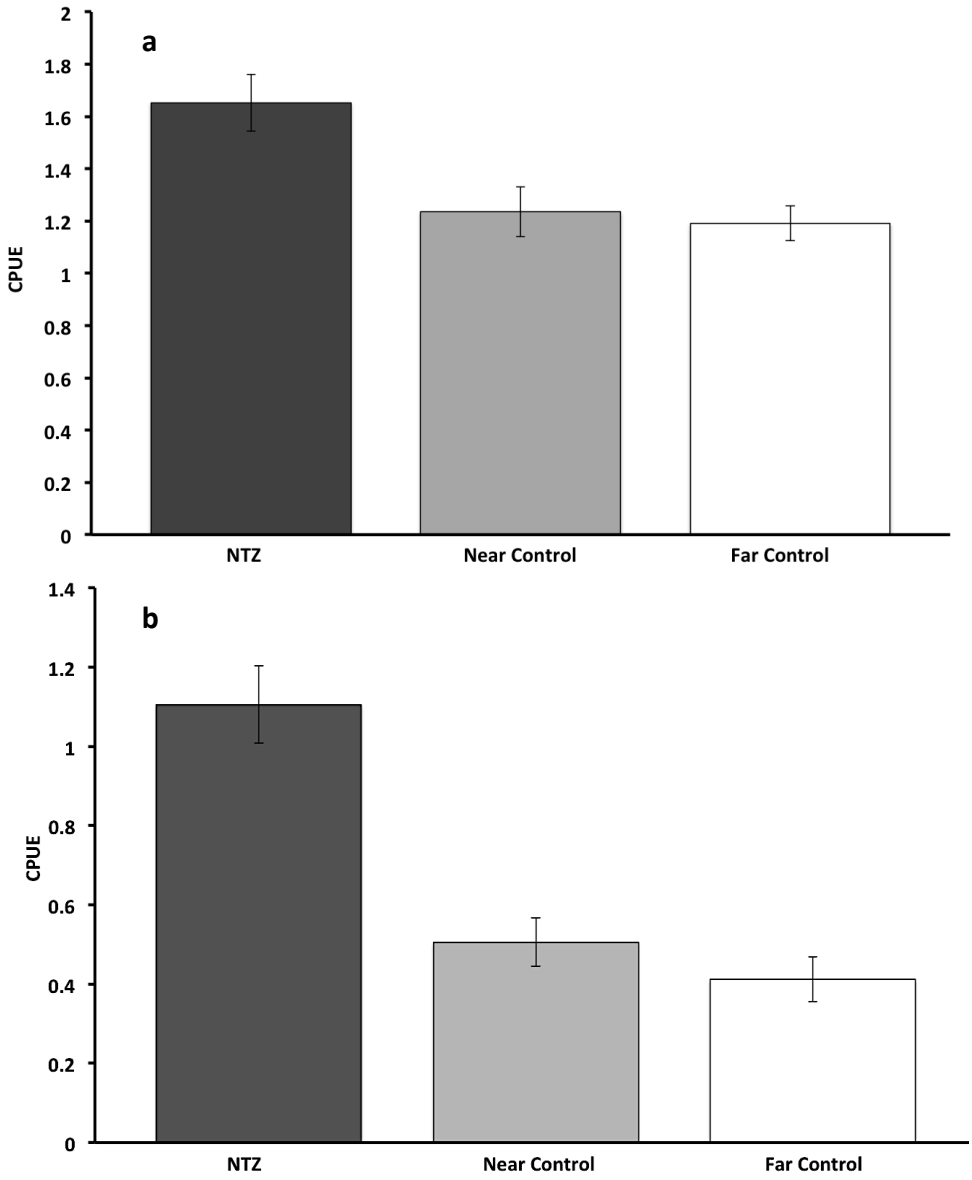


Figure 4. The mean number of **(a)** lobster and **(b)** legal lobster caught per pot in the NTZ, Near Control and Far Control (±SE).

Table 1. Summary of the results obtained from lobster populations in the NTZ, Near Control and Far Control populations during the July and August 2013 surveys.

Area	Mean CPUE	Mean Legal CPUE	Large lobster, %	Mean size (mm)	Mean legal size (mm)	Gender ratio (M:F)	Large females berried, %
NTZ *n=157*	1.653	1.105	66.88%	92.31	98.80	1:0.57	23.91
Near Control *n=233*	1.235	0.506	41.20%	85.07	93.33	1:0.75	10.52
Far Control *n=381*	1.191	0.413	34.65%	*n/a*	94.23	1:0.54	31.11

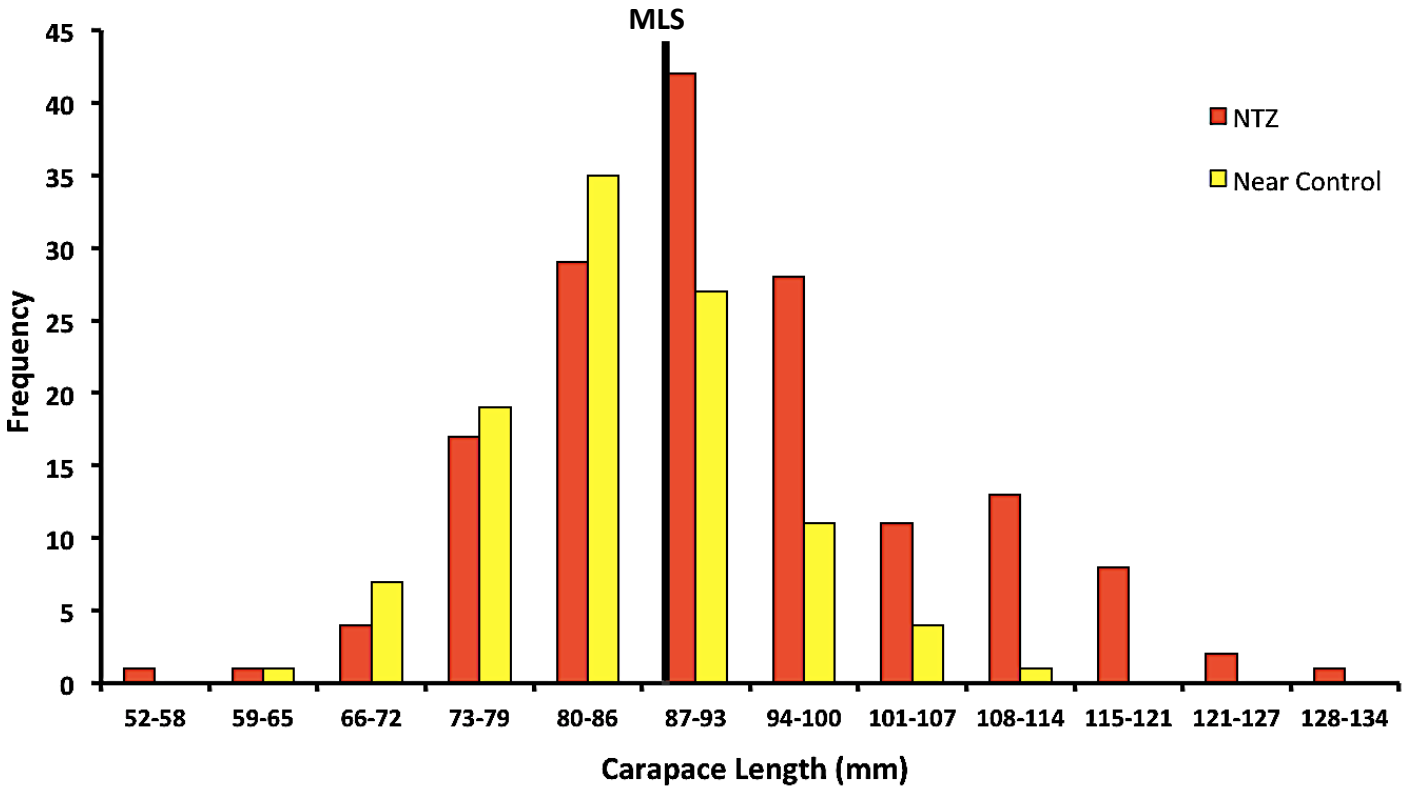
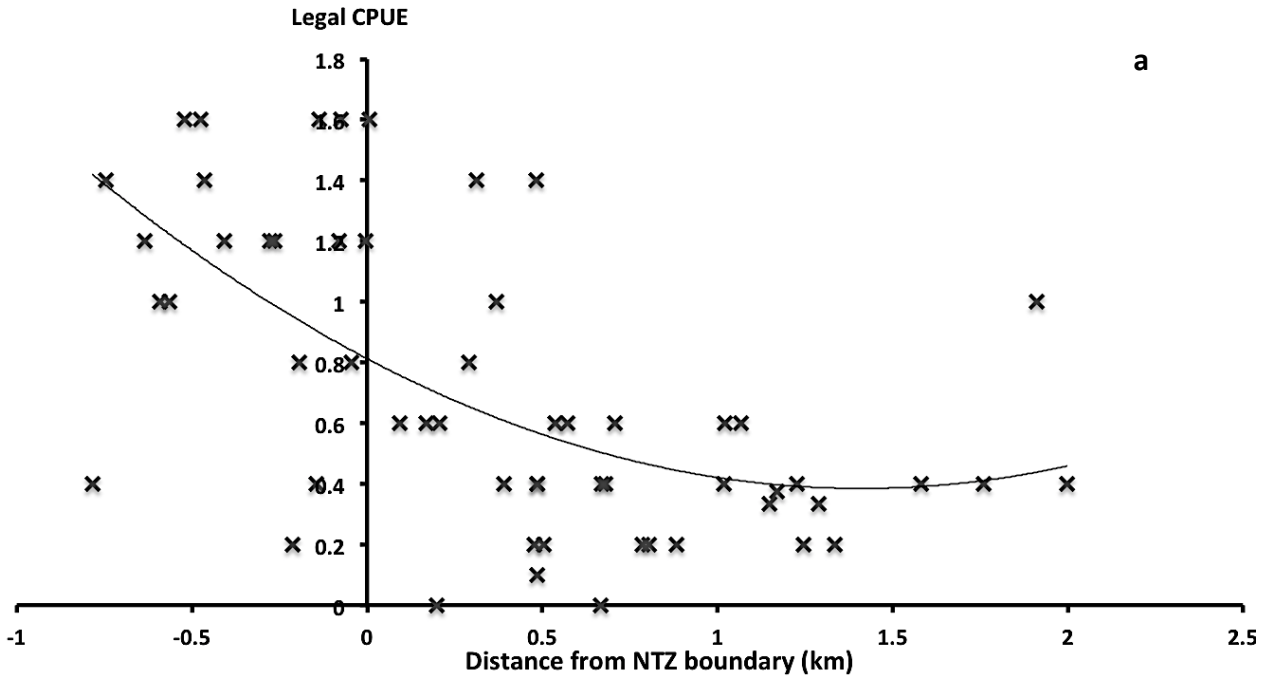


Figure 5. The size distribution of lobsters in the NTZ (n=157) and Near Control (n=105) caught during the July and August 2013 sampling surveys, with the minimum landing size (MLS; ≧87mm CL) highlighted.

Lobster CPUE shows a significant negative correlation with distance from the NTZ boundary (Spearman's rank correlation, r=-0.560, d.f.=54, p>0.0001; Figure 6a). The mean CPUE per string increased with greater distance inside the NTZ, with a reduction and eventual plateau in CPUE evident as distance from the NTZ boundary increased (Figure 6a). This relationship is weakened with the inclusion of the Far Control data (Figure 6b), although it remains statistically significant (Spearman's rank correlation, r=-0.398, d.f.=92, p>0.0001) and provides a baseline CPUE further from the NTZ of approximately 0.5.



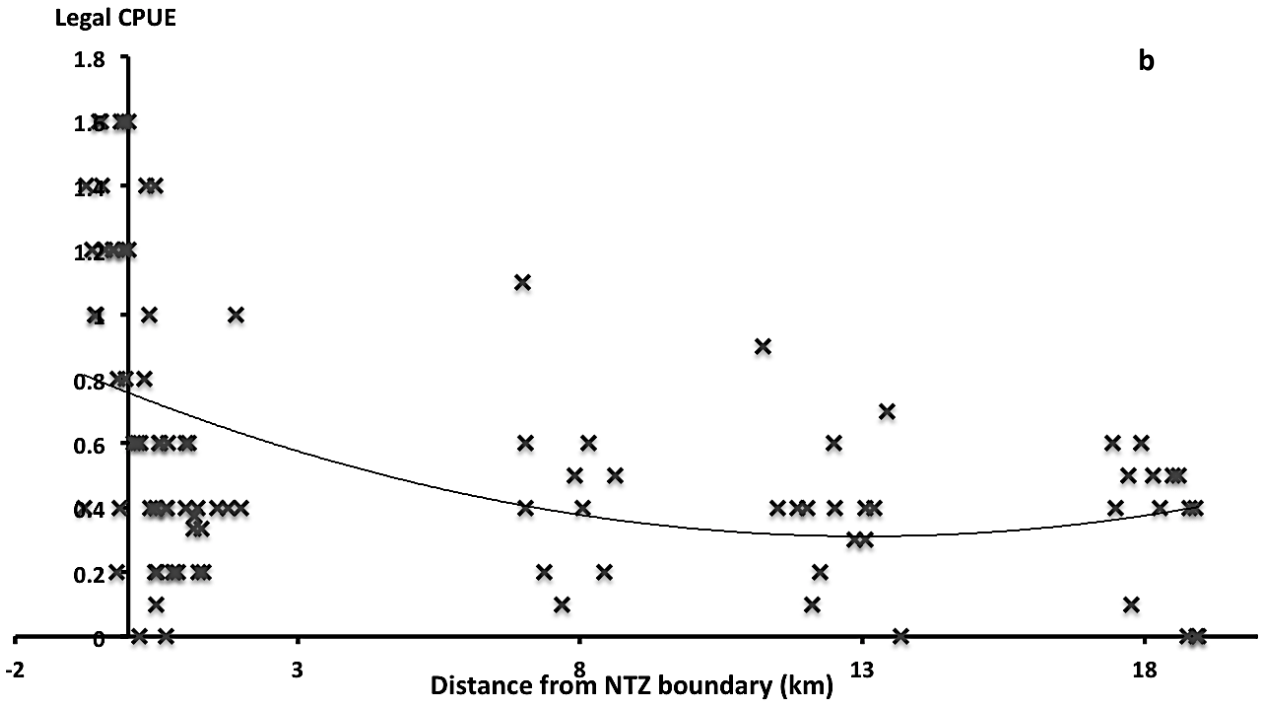


Figure 6. (a) The mean number of legal (≧87mm CL) lobster caught per pot from the NTZ and Near Control in each string, plotted against the distance (km) that each string lies from the nearest boundary of the NTZ, fitted with a polynomial regression line (r^2=0.37493). **(b)** The mean number of legal-sized lobster caught per pot in the NTZ, Near and Far Control in each string, fitted with a polynomial regression line (r^2=0.194). Negative x-values indicate strings deployed inside the NTZ, while the y-axis represents the boundary line of the NTZ.

- Brown crab

The highest abundance of brown crab was recorded in the Far Control, where mean CPUE was 325.17% higher than that of the NTZ (0.625 vs. 0.147, unpaired T-test, $p<0.0001$; Figure 7a and Table A5). Similarly, brown crab was 204.08% more abundant in the Near Control compared to the NTZ (0.437 vs. 0.147, unpaired T-test, $p=0.0003$; Figure 7a and Table A4). This represents 6.45% decrease in the NTZ over the preceding 12-month period (0.157 to 0.147) and a 34.46% increase in the Near Control over the same period (0.325 to 0.437).

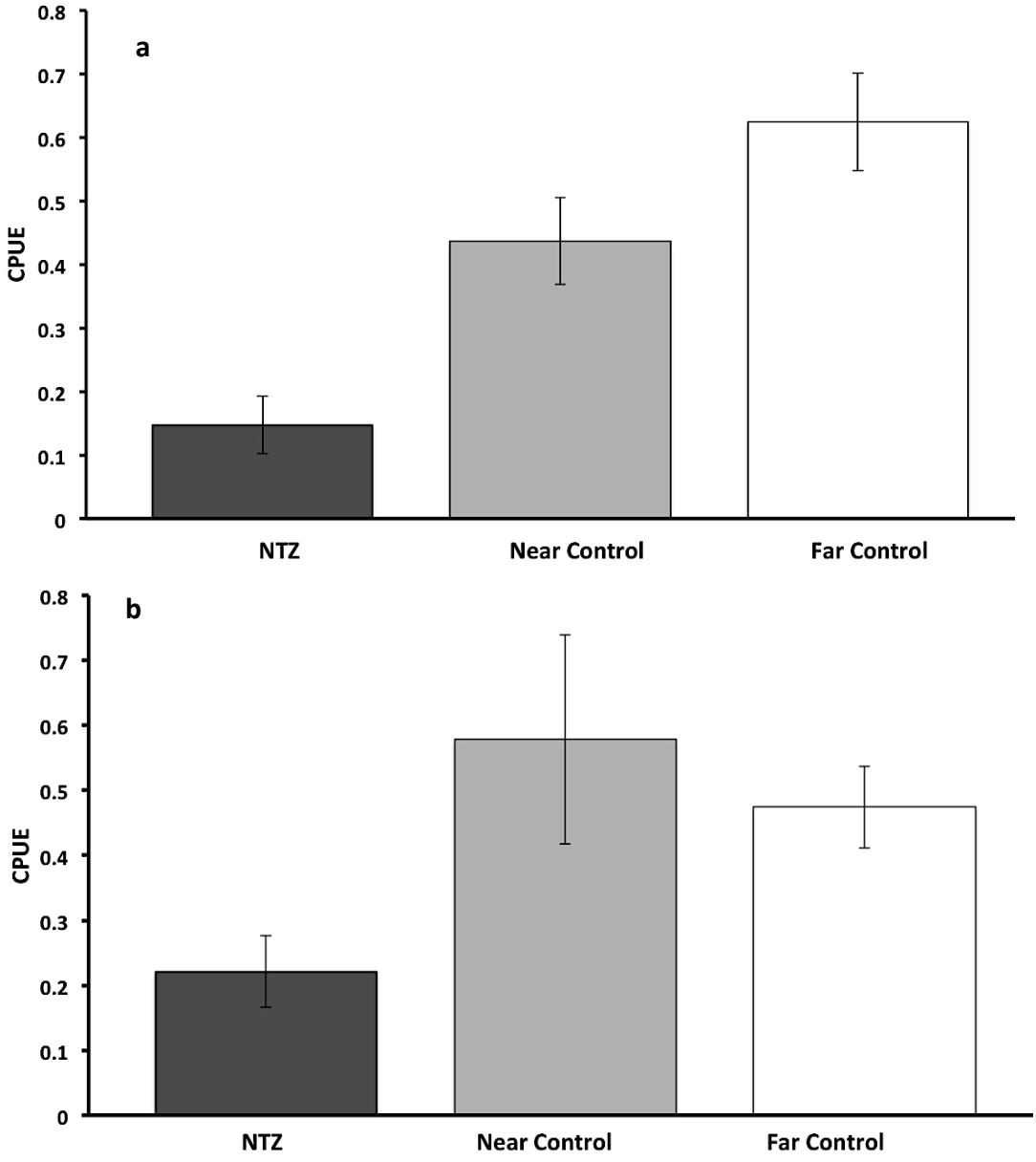


Figure 7. The mean number of **(a)** brown crab and **(b)** velvet crab caught per pot in the NTZ, Near Control and Far Control (±SE).

- *Velvet crab*

Mean CPUE of velvet crab was 161.7% higher in the Near Control than the NTZ (unpaired T-test, p=0.032; Figure 7b and Table A4) and 114.7% higher in the Far Control than the NTZ (unpaired T-test, p=0.254; Figure 7b and Table A5). This represents a reduction of 81.13% in abundance in the NTZ over the preceding 12-month period (1.261 to 0.221) and a 12.78% increase in the Near Control over the same period (0.512 to 0.558).

- Mean size (aim 3)

- *Lobster*

The mean size of lobster caught in the NTZ was 8.52% larger than those from the Near Control during the sampling surveys (unpaired T-test, p<0.0001; Table A1). Although direct comparisons of overall mean size could not be drawn between the NTZ and Far Control due to the sampling method used during fishing observations, the mean legal size was 4.85% higher in the NTZ compared to the Far Control (unpaired T-test, p<0.004; Table A2) and 6.34% higher compared to the Near Control (unpaired t-test, p=0.0007; Table A1).

The mean size of lobster showed a significant negative correlation with distance from the NTZ boundary (Spearman's rank correlation, r=-0.610, d.f.=34, p>0.0001; Figure 8). The mean CL per string increases with distance inside the NTZ, while a reduction in mean CL per string is evident within the Near Control as distance from the NTZ boundary increases (Figure 8). The mean size inside the NTZ increased by 1.56% from that of the 2012 sampling surveys (90.89mm to 92.31mm), although mean legal size decreased by 1.99% over the same period (100.81mm to 98.8mm). Mean size in the Near Control remained constant (85.03mm to 85.07mm), although mean legal size decreased by 1.65% (94.47mm to 92.91mm).

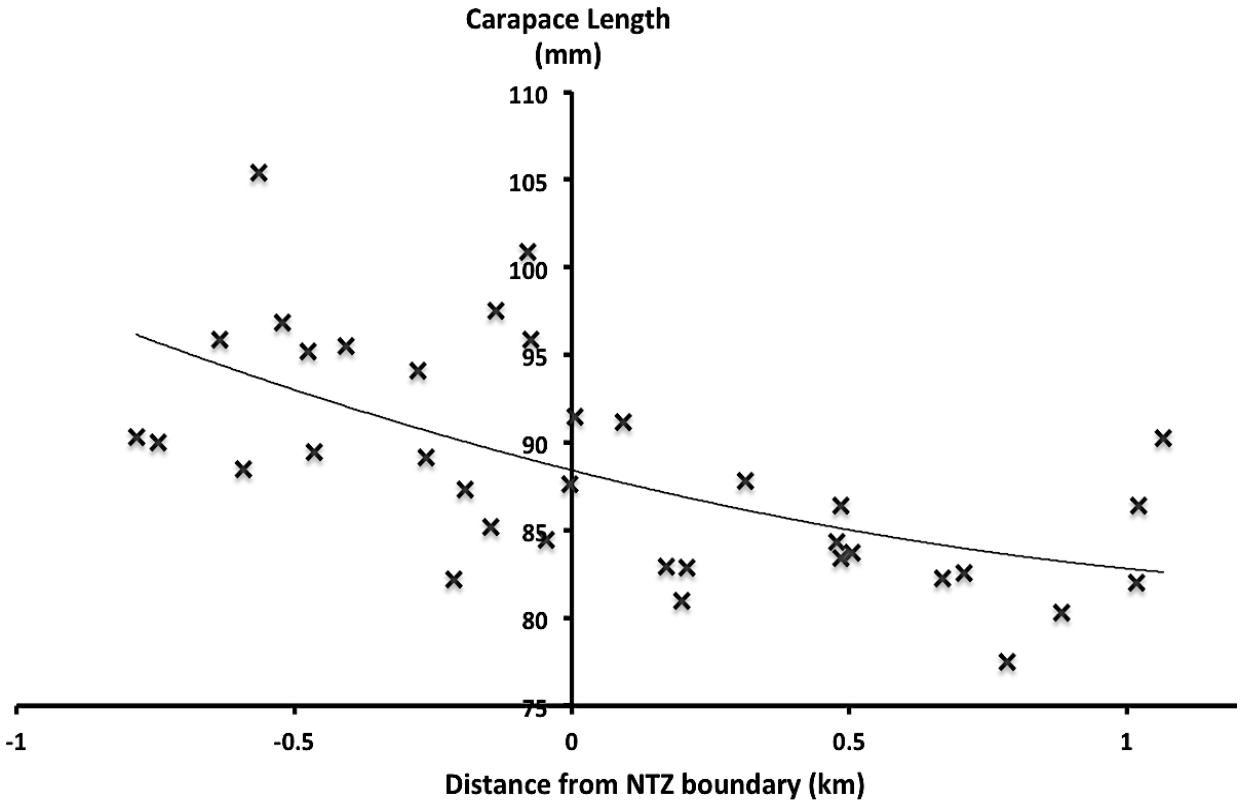


Figure 8. The mean carapace length (mm) of lobster per string from the July and August 2013 sampling surveys in the NTZ and Near Control, plotted against the distance (km) that each string lies from the nearest boundary of the NTZ, fitted with a polynomial regression line (r^2=0.38262). Negative x-values indicate strings deployed inside the NTZ, while the y-axis represents the boundary line of the NTZ.

- *Brown crab*

The mean size of brown crab was 8.64% larger in the Near Control compared to the NTZ, although this difference was statistically insignificant (unpaired T-test, p=0.280; Table A4). From July 2012 to August 2013 mean brown crab size inside the NTZ decreased by 6.93% (125.25mm to 116.57mm), while change in the Near Control was minimal, with a decrease of 1.68% (128.81mm to 126.64mm).

- *Velvet crab*

The mean size of velvet crab was 2.92% larger in the NTZ compared to the Near Control, although this difference was statistically insignificant (unpaired T-test, p=0.085; Table A4). This represents a reduction of 0.89% in mean size over the last 12 months (68.89mm to 68.29mm).

- Lobster health (aim 4)

- *Berried females*

Berried females were 127.17% more abundant in the NTZ compared to the Near Control. This difference, however, proved to be statistically insignificant (Fisher's exact test, p=0.189; Table A1). Berried females in the Far Control were 30.11% more abundant compared to the NTZ (Fisher's exact test, p=0.263; Table A2).

- *Damage and disease*

Lobster in the NTZ had higher incidences of damage to the exoskeleton and absence of legs and/or claws, while lobster in the Near Control had higher rates of damage to the antennae and a higher proportion of regrown claws or legs (Figure 9). Despite these variations, all factors were insignificant when tested with a Fisher's exact test ($p>0.05$; Table A7 and A8). Shell disease was not encountered in the Near Control, whereas in the NTZ four lobsters (5%) displayed signs of shell disease (Figure 9). Shell disease was only present in large males (mean CL 115.5mm) primarily on the claws and tail. This difference, however, proved to be statistically insignificant (Fisher's exact test, p=0.059). Further tests conducted on the prevalence of disease and injury divided by size and gender showed that a significantly higher proportion of small females (<87mm CL) in the Near Control had, or were undergoing, regrowth of an arm or leg, compared to small females in the NTZ (Fisher's exact test, p=0.046; Table A8). All other Fisher's exact tests proved insignificant ($p>0.05$).

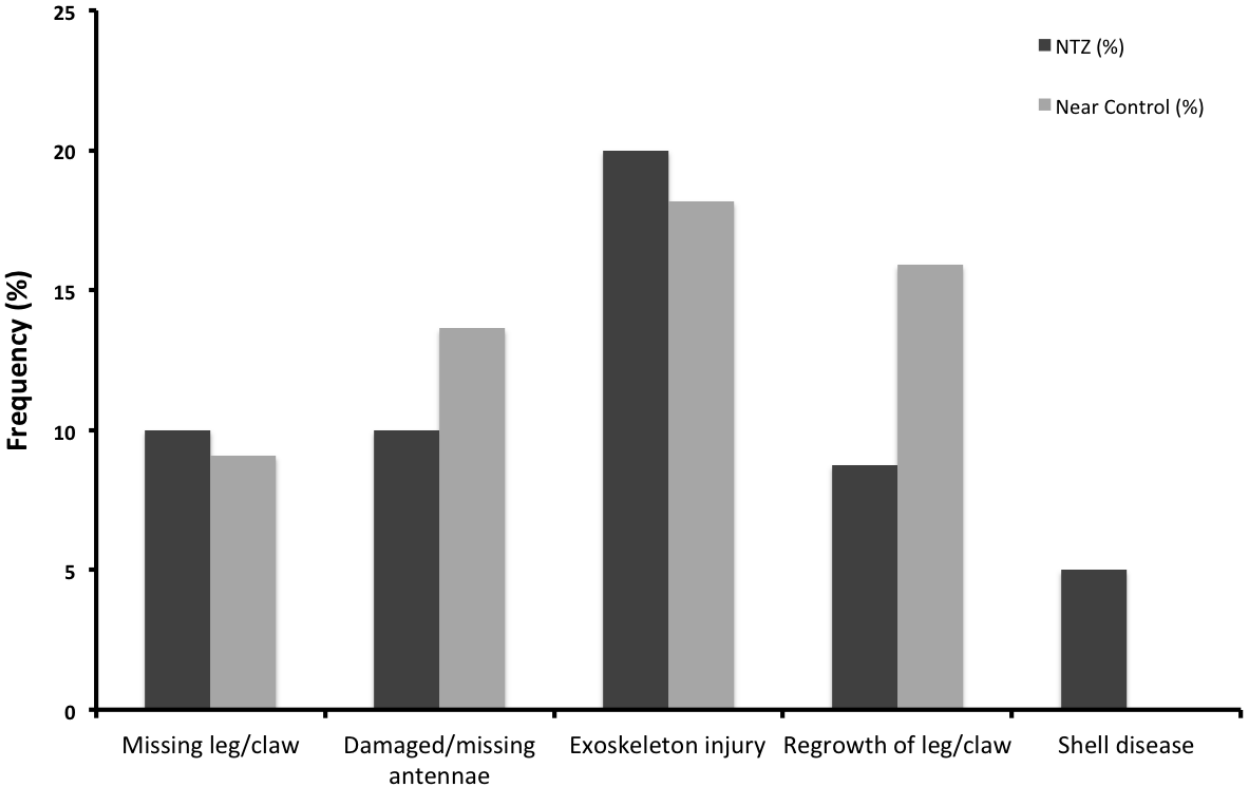


Figure 9. The frequency of disease and injuries encountered for lobsters sampled from the NTZ (dark grey; n=80) and Near Control areas (light grey; n=44) during the August 2013 sampling surveys.

- Tagging and recapture

During the July surveys a total of 131 lobsters were tagged – 70 from the NTZ and 61 from the Near Control, with a further 102 tagged during the August 2013 surveys – 60 from the NTZ and 42 from the Near Control. Due to a limited number of tags and lack of recaptures, brown crabs were only tagged during the first two days of the July surveys – totalling four from the NTZ and 22 from the Near Control. When combined with the 2012 surveys, a total of 441 lobsters were tagged – 234 from the NTZ and 207 from the Near Control, with a total of 68 brown crab tagged – 28 from the NTZ and 40 from the Near Control.

- Recaptures

In the 12-month period following the August 2012 surveys, a total of 29 lobster recaptures were recorded – 59% from the 2013 fishing surveys and the remaining 41% through reports from commercial and recreational creelers. These recaptures comprised 27 unique individuals, representing a recapture rate of 6.12%. 11 of the 27 lobsters had moulted, and therefore grown, during the interval between tagging and recapture, all of which were initially tagged within the NTZ and nine of which had

remained inside the NTZ. This represented a mean growth rate of 11.54%. The absolute minimum distance travelled per lobster ranged from 0.008km to 7.050km, with a mean minimum distance of 0.751km. Lobster initially tagged inside the NTZ typically displayed lower levels of movement and higher site fidelity compared to the Near Control, although this difference was insignificant (median distance travelled 104m *vs.* 214m; unpaired t-test, p=0.1946). Two lobsters travelled from the NTZ to the Near Control, representing a movement rate of 0.85% out of the NTZ; although a further two lobsters travelling from the Near Control into the NTZ, producing a net movement rate of zero. Over the same period no brown crab recaptures were recorded.

Discussion

- Abundance

Following five years of protection, lobster populations within Lamlash Bay NTZ appear to be showing significant and measurable signs of recovery. Higher abundance of lobster, larger mean size and considerably higher abundance of larger individuals inside the NTZ relative to both the Near and Far Control is a classic response following the cessation of fishing pressure (Lester et al., 2008). This reaffirms findings by Hoskin et al. (2011) and Wootton et al. (2012), who showed a similar response for lobster, albeit of a greater magnitude, following the cessation of fishing in Lundy Island NTZ, England. Their studies found lobster to be 500% and 771% more abundant, respectively, relative to nearby control locations, compared to just 33.8% herein. This disparity, however, appears to be fuelled mainly by significantly lower abundance of lobster in nearby control locations at Lundy. Wootton et al. (2012) report a mean CPUE of 0.117 in the nearby refuge zone, whereas the mean CPUE of lobster in the Near Control at Lamlash Bay NTZ totalled 1.235. Similarly, average CPUE within Lamlash Bay NTZ (1.653) was higher than that of Lundy (1.364), suggesting that the area may be naturally more productive.

Two lobsters were recorded 'spilling over' from the NTZ into the openly fished Near Control zone, representing an export rate of 0.85%. This is somewhat lower than other studies, with Huserbråten et al. (2013) showing an export rate of 4.7% and Øresland and Ulmestrand (2013) an export rate of 1.4% for lobster in Swedish reserves. This difference is likely due to the comparatively lower fishing pressure surrounding Lamlash Bay NTZ, and hence less lobster originating from the NTZ are encountered by fishermen, although it may also be attributable to the relatively high rate of site fidelity seen within the NTZ, resulting in reduced movement of lobster outwards. A further two lobster were recorded moving into the NTZ, thus producing a net movement of zero between the NTZ and Near Control, although such a small sample size renders the evidence anecdotal at best. However, the relationship between CPUE and distance from the reserve boundary suggests that spillover of lobsters from the NTZ into surrounding waters may be occurring, as elevated catch levels are evident within approximately 350m of the reserve boundaries relative to baseline levels in the Far Control – a spillover distance similar in magnitude to that recorded for fish species from other European protected

areas (Harmelin-Vivien et al., 2008). The increase in abundance of lobster within the NTZ from 2012-2013 suggests that vacant territory still exists within the NTZ, which is being occupied over time. In coming years the amount of available territory is likely to decrease, and with it the increase in lobster abundance inside the NTZ will slow. At this point it is likely that spillover into surrounding waters will accelerate, as available territory becomes a limiting factor and lobsters are forced to migrate outwards – a process known as density-dependent migration (Abesamis and Russ, 2005).

Despite being protected from fishing mortality, both brown and velvet crab were significantly less abundant within the NTZ, where lobster abundance was highest. Conversely, the highest abundance of brown crab was recorded in the Far Control, where abundance of lobster was lowest. This appears to suggest that higher density of lobster within the NTZ is supressing abundance of both crab species, either through direct predation or increased competition for habitat space and food resources (Hoskin et al., 2011). An alternative explanation is that the relationship arose as a quirk of the sampling method employed - brown and velvet crab may be less likely to enter creels within the NTZ as the mean number of lobster here, a significant predator, is higher per creel (Hoskin et al., 2011). Based on observations during the surveys and observations, however, this did not appear to be the case, as both crab species were frequently encountered in the same creel as lobsters. Another explanation is that the higher rates of movement in brown crab may render them more at risk of fishing mortality than lobster, as the lack of any recaptures from the tagging study indicates the high level of migration that this species undertakes. A past tag and recapture study by Fahy and Carroll (2009) showed migration by two females of 245km and 269km, in 689 days and 1758 days, respectively. Considering the small size of Lamlash Bay NTZ (2.67km^2) it is likely that individual crabs receive minimal, if any, protection in the long-term. This does, however, fail to explain the disparity between the NTZ and control locations, as both populations in the control locations are also unprotected due to their location within actively fished waters.

- Mean size

Of the three target species, only lobster showed a significant increase in size that is attributable

to the NTZ. The mean size of lobster inside the NTZ increased over the proceeding 12 months, suggesting that the population is still undergoing recovery towards a natural, unexploited state. The mean size of legal-sized individuals, did, however, decrease over the same period, possibly as a result of mortality or net migration out of larger individuals. The NTZ harbours significantly higher numbers of larger individuals (>100mm CL) than the Near Control, with 35 captured in the NTZ during sampling surveys, compared to just five in the Near Control. The NTZ is therefore safeguarding against longevity overfishing, whereby the largest individuals within open waters are removed (Diekert, 2012). This has a significant impact on reproductive potential of the respective populations, as the largest individuals contribute disproportionately to the overall reproductive potential of a population (Tully et al., 2001; Lizarraga-Cubedo et al., 2003; Agnalt, 2008). That the mean size of lobster is elevated within close proximity to the NTZ provides further support for spillover occurring in the form of smaller individuals migrating outwards from the reserve, establishing territory in areas of lower density and therefore lower competition (Hoskin et al., 2011). This phenomenon is similar to that noted by Abesamis and Russ (2005) in a long-term study involving a species of tropical reef fish.

- Disease

There were no significant trends with regards frequency of disease or injury of lobster inside the NTZ relative to those in the Near Control. This is in contrast to Wootton et al. (2012) who concluded that greater densities of lobster inside Lundy Island NTZ were fuelling higher prevalence of shell disease and physical injury. The only metric found to be significant herein showed the rate of claw/leg regrowth within small female lobster to be significantly higher outside the NTZ. Consequently, there appears to be no evidence at present that lobster populations within Lamlash Bay NTZ are suffering higher rates of injury or disease as a result of higher densities.

Conclusion

Increases in lobster abundance prior to the designation of the NTZ cannot be definitively proved due to the absence of a before-after control-impact (BACI) design. Monitoring of future MPAs would benefit greatly from ensuring that this approach is implemented and followed (Moland et al., 2013). Despite this, the findings from this study demonstrate that lobster populations can increase significantly and at a rapid pace, relative to fished waters, if afforded complete protection. That this response has been observed in such a small reserve relative to many others worldwide demonstrates the effectiveness that even small conservation measures can have if suitably applied and enforced. Further study of the site over the long-term is essential to gain a better understanding of the degree to which spillover and larval export from the reserve may be occurring, in addition to monitoring of the health of lobster populations inside the NTZ as densities increase.

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Additional activities

In addition to performing my main surveying work throughout the summer, I also performed extra activities involving engagement with the local community through COAST-run events, including:

- Helping to set up COAST touch tank aquariums for the Lamlash Gala Day on 13th July
- Engaging with the general public at the Brodick Tourist Office Touch Tank (17th July) and Lamlash Agricultural Show (7th August), educating both children and adults on animals found in Lamlash Bay through demonstrations in the touch tanks as well as furthering awareness of the NTZ and COAST as an organisation, signing people up to the COAST newsletter to receive more information about the organisation and completing questionnaires to provide support for the designation of the South Arran MPA.
- Assisting in running a seashore scramble at Kildonan (16th August), which provided children and parents with the opportunity to learn more about animals found on British shores. I helped groups to find animals, identified and explained about the animals found and furthered awareness of COAST.

Photos from COAST-run community events. The Lamlash Bay Agricultural Show (top left, top right), Kildonan seashore scramble (bottom left) and Brodick touch tank day (bottom right).

Appendix

Table A1. Statistical analysis of the main lobster metrics in the NTZ *vs.* Near Control zone

Variable	NTZ	Near Control	Statistical test	*P*
Mean CPUE	1.653	1.235	Unpaired t-test	**0.0027**
Mean Legal CPUE	1.105	0.506	Unpaired t-test	**0.0001**
Large lobster, %	66.88	41.20	Fisher's Exact test	**0.0006**
Mean size (mm)	92.31	85.07	Unpaired t-test	**0.0001**
Mean legal size (mm)	98.80	93.33	Unpaired t-test	**0.0007**
Gender ratio (M:F)	1:0.57	1:0.75	Fisher's Exact test	0.291
Large females berried, %	23.91	10.52	Fisher's Exact test	0.189

Table A2. Statistical analysis of the main lobster metrics in the NTZ *vs.* Far Control zone

Variable	NTZ	Far Control	Statistical test	*P*
Mean CPUE	1.653	1.191	Unpaired t-test	**0.0002**
Mean Legal CPUE	1.105	0.413	Unpaired t-test	**<0.0001**
Large lobster, %	66.88	34.65%	Fisher's Exact test	**<0.0001**
Mean size (mm)	92.31	*n/a*	Unpaired t-test	*n/a*
Mean legal size (mm)	98.80	94.23	Unpaired t-test	0.4725
Gender ratio (M:F)	1:0.57	1:0.54	Fisher's Exact test	0.901
Large females berried, %	23.91	31.11	Fisher's Exact test	0.246

Table A3. Statistical analysis of the main lobster metrics in the Near Control *vs.* Far Control zone

Variable	Near Control	Far Control	Statistical test	*P*
Mean CPUE	1.235	1.191	Unpaired t-test	0.708
Mean Legal CPUE	0.506	0.413	Unpaired t-test	0.147
Large lobster, %	41.20	34.65%	Fisher's Exact test	0.121
Mean size (mm)	85.07	*n/a*	Unpaired t-test	*n/a*
Mean legal size (mm)	93.33	94.23	Unpaired t-test	0.3416
Gender ratio (M:F)	1:0.75	1:0.54	Fisher's Exact test	0.216
Large females berried, %	10.52	31.11	Fisher's Exact test	**0.006**

Table A4. Statistical analysis of the main brown crab (B) and velvet crab (V) metrics in the NTZ *vs.* Near Control zone

Variable	Sp	NTZ	Near Control	Statistical test	*P*
Mean CPUE	B	0.147	0.437	Unpaired t-test	**0.0005**
	V	0.221	0.578		**0.0461**
Mean Legal CPUE	B	0.004	0.224	Unpaired t-test	**0.0001**
	V	0.155	0.494		0.138
Large crab, %	B	28.57	42.22	Fisher's Exact test	0.053
	V	71.42	66.67		0.538
Mean size (mm)	B	116.57	126.64	Unpaired t-test	0.2798
	V	68.29	66.35		0.085
Mean legal size (mm)	B	146.25	159.07	Unpaired t-test	0.14
	V	70.53	68.59		0.209
Gender ratio (M:F)	B	1:0.2	1:0.55	Fisher's Exact test	0.303
	V	1:0.05	1:0.37		**0.034**

Table A5. Statistical analysis of the main brown crab (B) and velvet crab (V) metrics in the NTZ *vs.* Far Control zone

Variable	Sp	NTZ	Far Control	Statistical test	*P*
Mean CPUE	B	0.147	0.625	Unpaired t-test	**0.0005**
	V	0.221	0.474		0.254
Mean Legal CPUE	B	0.004	0.251	Unpaired t-test	**0.0001**
	V	0.155	n/a		n/a
Large crab, %	B	28.57	25.71	Fisher's Exact test	0.748
	V	71.42	n/a		n/a
Mean size (mm)	B	116.57	n/a	Unpaired t-test	n/a
	V	68.29	n/a		n/a
Mean legal size (mm)	B	146.25	157.17	Unpaired t-test	0.287
	V	70.53	n/a		n/a
Gender ratio (M:F)	B	1:0.2	1:0.39	Fisher's Exact test	0.494
	V	1:0.05	n/a		n/a

Table A6. Statistical analysis of the main brown crab (B) and velvet crab (V) metrics in the Near Control *vs.* Far Control zone.

Variable	Sp	Near Control	Far Control	Statistical test	*P*
Mean CPUE	B	0.437	0.625	Unpaired t-test	**0.0287**
	V	0.578	0.474		0.155
Mean Legal CPUE	B	0.224	0.251	Unpaired t-test	0.901
	V	0.494	n/a		n/a
Large crab, %	B	42.22	25.71	Fisher's Exact test	**0.016**
	V	66.67	n/a		n/a
Mean size (mm)	B	126.64	n/a	Unpaired t-test	n/a
	V	66.35	n/a		n/a
Mean legal size (mm)	B	159.07	157.17	Unpaired t-test	0.876
	V	68.59	n/a		n/a
Gender ratio (M:F)	B	1:0.55	1:0.39	Fisher's Exact test	0.516
	V	1:0.37	n/a		n/a

Table A7. Statistical output of Fisher's Exact Test results for the main disease and injury metrics for males/females in the NTZ *vs.* Near Control zone

Size/gender	Area	Missing leg/claw, %	Damaged/ missing antennae, %	Exoskeleton damage, %	Regrown claw/leg, %	Shell disease, %
Male	NTZ *n=34*	11.76	8.82	29.41	11.76	11.76
	Near *n=27*	16.00	20.00	24.00	12.00	0
		p=1	*p=1*	*p=0.118*	*p=0.492*	*p=0.122*
Female	NTZ *n=25*	11.11	11.11	11.11	18.52	0
	Near *n=17*	5.88	17.65	17.65	29.41	0
		p=0.632	*p=1*	*p=0.716*	*p=0.23*	*p=1*

Table A8. Statistical output of Fisher's Exact Test results for the main disease and injury metrics for small and large males/females in the NTZ *vs.* Near Control zone

Size/gender	Area	Missing leg/claw, %	Damaged/ missing antennae, %	Exoskeleton damage, %	Regrown claw/leg, %	Shell disease, %
Small Male	NTZ *n=14*	0	0	14.29	14.29	0
	Near *n=19*	15.79	10.53	10.53	26.32	0
		p=0.244	*p=0.496*	*p=0.99*	*p=0.670*	*p=1*
Large Male	NTZ *n=20*	20	15	40	10	20
	Near *n=8*	0	12.5	12.5	0	0
		p=0.295	*p=0.98*	*p=0.214*	*p=1*	*p=0.294*
Small Female	NTZ *n=11*	27.27	36.36	27.27	0	0
	Near *n=14*	0	14.29	14.29	35.71	0
		p=0.07	*p=0.33*	*p=0.623*	***p=0.046***	*p=1*
Large Female	NTZ *n=14*	7.14	7.14	21.43	21.43	0
	Near *n=3*	33.33	33.33	33.33	0	0
		p=0.33	*p=0.33*	*p=0.99*	*p=0.97*	*p=1*

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