Blow lug *Arenicola marina* density in the Severn Estuary European Marine Site: A baseline survey 2012-2013

Dr Libby Ross
Senior Environment Officer
Devon and Severn Inshore Fisheries and Conservation Authority
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Table of Contents

Executive Summary

Blow lug, *Arenicola marina* is a popular bait species for many sea anglers throughout the Devon and Severn Inshore Fisheries and Conservation Authorities' (D&S IFCA) district. In the Severn area it is the second most popular bait used by recreational sea anglers. Of the lugworm used by anglers in the Severn 68% is bought from shops (the majority of which will be farmed) and 32% is dug locally. Lugworm is dug from Minehead all the way through to the most northerly population of lugworm in the Severn, at Sharpness.

Much of the activity is focused around five large sandy beaches within the Severn Estuary Special Area of Conservation (SAC) and Special Protection Area (SPA): Burnham-On-Sea, Berrow, Brean, Weston-Super-Mare and Sand Bay. These beaches form part of the Intertidal Mudflat and Sand Flat feature of the SAC, which is also a supporting habitat for many of the bird species of the SPA. *Arenicola marina* is specified in the conservation advice provided by Natural England as one of the key species of the community of this feature. The conservation objectives relating to this feature for the SAC include no decrease in extent or range of types of intertidal mudflat and sandflat communities from an established baseline, no decline in community quality due to changes in species composition or loss of typical species from an established baseline, subject to natural processes. For the SPA the conservation objective is no deviation in the presence and abundance of suitable prey species from an established baseline. Therefore Devon & Severn IFCA identified the need for a dedicated bait density survey, to establish a working baseline for *A.marina* populations and to assess the vulnerability of the beaches to bait digging pressures.

The results of the survey found that overall, mean and maximum *A.marina* densities in the Severn Estuary are within the realms of those found at other UK sites, albeit at the lower end. Lugworm density populations found in 2012-2013 agree closely with those from the only other published study of *A.marina* density in the Severn Estuary, carried out in 1972. This suggests lugworm populations are relatively stable in the Severn. Variation was found between the five study sites in terms of mean and maximum densities, with a maxima of both variables found at Brean, possibly relating to sediment particle size. The along-transect differentiation of adult and juvenile populations was highly variable within and between beaches, with some evidence of upper shore 'nursery' areas at the northern ends of Brean and Weston-Super-Mare. Elsewhere no such differentiation was observed, possibly relating to the patchiness of mud relative to suitable sandy mud habitat. Finally, an unexpected and unprecedented pattern in the ratios of adult and juvenile lugworm was observed between beaches. Stepwise in a northern direction from Burnham-On-Sea to Sand Bay there was an appreciable decrease in the proportion of juvenile lugworm, and corresponding increase in the proportion of adult lugworm. As no such pattern has previously been recorded, the reasons for this remain unclear. There are no current concerns regarding the densities of *Arenicola marina* in the Severn Estuary SAC, and therefore current levels of bait digging are deemed sustainable. However long-term monitoring is necessary to provide a baseline data set which can provide sufficient resolution to detect anthropogenic differences from natural ones, should a future increase in bait digging activity occur.

1. Introduction

This study investigates the distribution and density of the benthic polychaete *Arenicola marina*, in the Severn Estuary, UK. *A.marina* is a subsurface deposit feeder common on sandflats throughout Northern Europe (Hardege et al. 1998). It is a member of the Polychaete family Arenicolidae which is comprised of 30 morpho-species in four genera. Two of these genera *Abarenicola* and *Arenicola* form the group of polychaetes commonly known as 'lugworms'. *Arenicola marina* or blow lug is one of the most researched tidal flat organisms (Görlitz 2011) due to its ecological, ecotoxicological and commercial importance as well as its broad distribution and locally high abundance.

1.1 Ecology

Arenicola marina builds mucus lined U-shaped burrows up to 40cm deep primarily in intertidal soft sediment (Görlitz 2011). Lugworms feed on sediment that subsides into their burrow, digesting organic matter (microalgae, meiofauna, bacteria and digestible detritus) associated with both the sediment grains and interstitial water (Riisgard & Banta 1998, Görlitz 2011). This behaviour has important ecological and physical implications, significantly affecting the abundance of other infaunal species (Flach and Beukema 1994, Hiddink 2002,) thereby shaping benthic community structure (Volkenborn 2007a). It is also an important ecosystem engineer, with bioturbation and bio-irrigation by the lugworm resulting in changed sediment biochemistry (Görlitz 2012). Results now suggest that through this bioturbation *A.marina* may be responsible for the maintenance of permeable sands, inhibiting the succession of intertidal habitats from sandflats with low organic content towards organic-enriched mudflats (Volkenborn 2007b&c). *A.marina* has also become an important bioindicator of a range of dissolved heavy metals and resuspended contaminants (Bird et al. 2011 Roberts 2012, Turner 2013).

Arenicola marina is an important prey item for many animals which forage in the intertidal and shallow subtidal zones. Although its deep-burrowing lifestyle minimises the risk of predation, *A.marina* is vulnerable when defecating on the sediment surface. Foraging fish and decapod crustaceans are common predators when lug are submerged accounting for 22% of total food intake in plaice, *Pleuronectes platessa*, in the Dutch Wadden Sea (de Vlas 1979). At low tide migratory shore birds such as curlew (*Numenius arquata*) and ringed plovers (*Charadrius hiaticula*) target lugworm (Pienkowski 1983). Much of this predation does not remove the whole lug, instead fish and birds demonstrate behaviour known as 'tail nipping', cropping only tip of the worm's tail, which is capable of regenerating (Bergmann et al. 1988). Nevertheless, 10-30% of annual production of *A.marina* may be removed by some form of predation (de Vlas 1979).

Within the Severn, *Arenicola marina* is unsurprisingly abundant at the seaward end, on the sandy shores in the Minehead area, but it can also be found in muddy sand on every beach up to Sharpness (Boyden and Little 1973). The salinity tolerance of juveniles is thought to be the limiting factor of *A.marina's* penetration any further up the estuary, whereas its distribution further seawards is limited by the availability of suitable habitat (Boyden & Little 1973).

1.2 Life history

Some of the most detailed studies of *Arenicola marina's* life history come from the Wadden Sea where it populates several thousand km^2 (Görlitz 2011). Adult *A.marina* spawn in early autumn to winter at low-water during spring tides (Flach and Beukema 1994, Watson 2000). Epidemic spawning (i.e. synchrous spawning of local populations of the same species) occurs, triggered by a combination of environmental cues. The exact timing will depend on the warmth of the early summer, the occurrence of a critical late-autumn drop in environmental temperature, and the arrival of suitable conditions – namely high pressure and associated dry, calm weather (Watson 2000). Juveniles overwinter in subtidal channels, hibernating in habitats such as shell gravel, or mussel beds (Riese et al. 2001). In the Wadden Sea, post-larvae 4-9mm long are present in the water column in the spring months (Flach and Beukema 1994).

During the spring to early summer juveniles settle on tidal flats and begin building their burrows, growing quickly, from about 1cm in early summer to approximately 5cm by the late summer (Flach and Beukema 1994). Experienced bait diggers and researchers alike have acknowledged the presence of zones of juvenile lug on the upper shore, which are known as nursery beds (Farke et al. 1979). Field studies have shown that juveniles will preferentially settle in areas with low adult densities (Flach and Beukema 1994). An area of very high density juveniles and a lower-than-average density of adults is present in the near-coastal zone in the Wadden Sea (Beukema 1992) and France (Pollack 1979). Similar results have been reported by anglers in the Severn, with nursery beds located higher up the shore relative to adult-dominated populations (D&S IFCA 2013a).

At the end of their first year many juveniles will undertake a 'long distance' down-shore migration, prompted by the high density of lugworm in the original bed settled in. They leave their burrow on an ebb tide at night, swimming in the water column and settling in the 'adult' lug beds. After this migration most lugworms will move only short distances for the rest of their life (Flach and Beukema 1994). By the second summer the juvenile lug will have reached adult size and weight, (Flach & Beukema 1994) and may live for an estimated 5-6 years (Howie 1984).

1.3 Bait use, commercial importance and potential environmental impacts

Blow lug is a popular bait species used by sea anglers throughout the UK. In the Severn it is favoured for targeting cod in the winter months and bass in the summer months. Data from interviews with sea anglers in the Severn suggest it is the second most popular bait within the study area (*Figure 1*). In total 53 out 125 anglers interviewed were using lug either by itself or in combination with other types of bait on the day they were fishing (D&S IFCA 2013a). The same survey revealed that approximately 32% of the lugworm used was collected (dug) by hand from the Severn area (*Figure 2*) the rest being supplied by local angling shops, usually in the form of farmed blow and black lugworm. The most popular beaches for digging lugworm were Minehead and Blue Anchor which are both South of the Severn Estuary European Marine Site (EMS) and five adjacent sandy beaches within the EMS; Burnham, Berrow, Brean, Weston-Super-Mare and Sand Bay. Olive (1993) identified three patterns of bait collection in Europe, private collection for primarily personal use, private collection by ad-hoc sellers to local retail outlets, and contracted collection with the bait going to a wholesaler outside of the area of collection (*Table 1*). Both Type I and Type II collection patterns have been revealed in the Severn through the D&S IFCAs bait digging interviews and close working with local anglers and bait shops. The level of Type II bait digging is low with only two individuals identified involved in such activities at the beaches studied in this report (D&S IFCA 2013a).

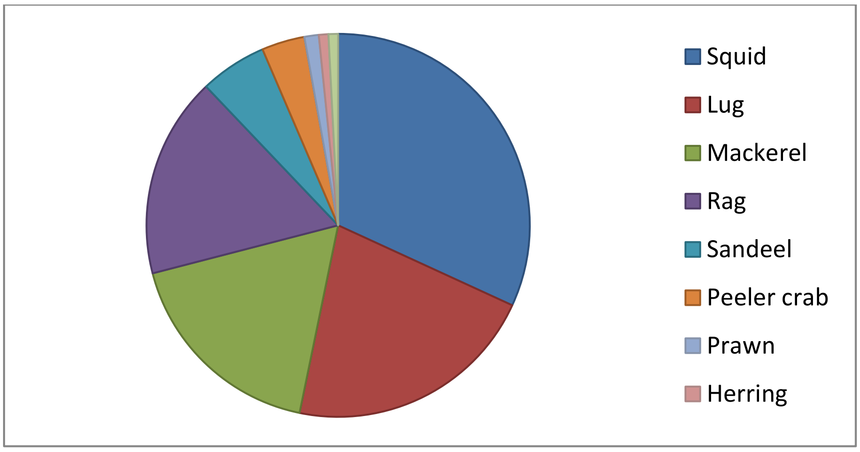

Figure 1. *The popularity of bait types used by sea anglers in the Severn. From additional data collected during interviews with sea anglers Feb 2012 - Feb 2013 as part of Sea Angling 2012*

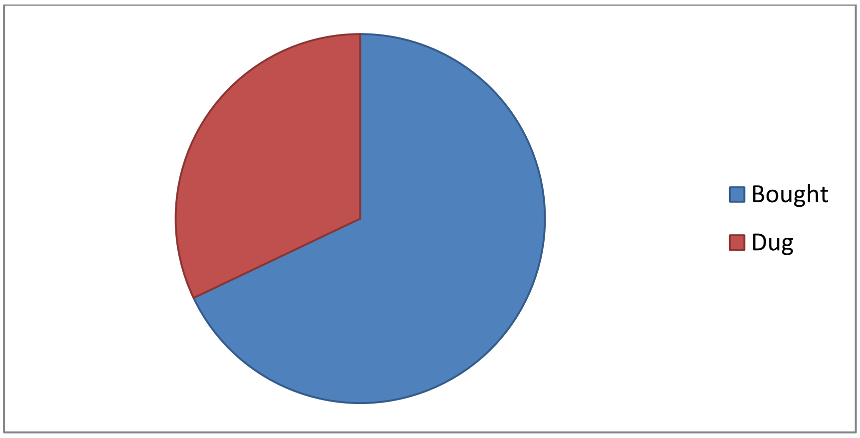

Figure 2. *The proportion of lugworm that is bought from angling and bait shops by sea anglers in the Severn compared to that which is dug from local beaches. From additional data collected during interviews with sea anglers Feb 2012 - Feb 2013 as part of Sea Angling 2012*

Bait digging may have a number of negative effects on the environment both *direct* and *indirect*. Direct effects generally relate to a reduction in or changes to characteristics of the lugworm population. Indirect effects include the burying and killing of other, sometimes commercially important, infauna such as cockles; increases in bioavailable heavy metals as result of disruption to the anoxic layer (Cryer et al. 1987); disturbance to bird populations; a reduction in prey abundance for birds and fish species which feed on lug (Olive 1993).

Table 1. *The three patterns of bait digging identified in Europe by Olive (1993)*

Exploitation Type	**Description**
Type I Private collection – own use	Bait collection by sea anglers primarily for their own use
Type II Private collection – *ad hoc* sales	Bait collection by semi-professional diggers supplying a variety of local retail outlets
Type III Contracted collection – contracted sales	Bait collection by professional bait diggers contracted to wholesalers distributing the materials to retailers outside the area of collection

Contrasting evidence exists as to the *direct* environmental effects of bait digging for lug worm. Relative to other exploited intertidal invertebrates, blow lug are relatively resilient to exploitation and disturbance because of their relative fecundity (Fowler 1999). However, a wide range of responses by *A.marina* to exploitation or experimental simulations of exploitation have been found, relating to local environmental conditions and the intensity and distribution of bait digging activity. Olive (1993) describes the scenario which led to complete removal of all lugworms from a large area of a National Nature Reserve in Northumberland in 1984, with densities falling from >40m^{-2} to <1m^{-2}. When the site was closed to bait digging it repopulated within a matter of months, thanks to the presence of extensive non-exploited populations nearby. Similarly lugworm populations in the Dutch Wadden Sea appear to be unaffected by large scale commercial exploitation, with an estimated 2 x 10^7 individuals take annually. However, Cryer et al. (1987) found no recovery in worm densities after 6 months following experimental removal, although natural densities at the test site in South Wales were low (9-16 m^{-2}) and the survey ran through the less productive winter months. The capacity of a population to withstand bait digging activities therefore relies on a number of factors including, the size of the exploited area relative to the total lug bed, the presence of other lug beds nearby, the presence of nursery areas, the relative exploitation of adult and juvenile lug, and the intensity and seasonality of bait digging.

Greater effort has been placed on determining the *indirect* effects of bait digging, and it is covered widely in the literature, so only a brief summary will be given here (see Fowler 1999 for a detailed review). Bait digging has been shown to cause physical damage, burial, smothering and/or exposure to desiccation or predation to non-target invertebrates. Recovery of small short-lived invertebrates will usually occur within a year but populations of larger, long-lived invertebrates may take much longer (Fowler 1999). In some extreme cases local diversity may be reduced, which may be especially true in physically fragile environments such as eelgrass or mussel beds (Fowler 1999). Bird disturbance is also a major concern, especially where peak bait digging coincides with peak bird abundance or intertidal activity (Townshend & O'Connor 1993). Reduced prey abundance by bait digging for lugworm has never been directly assessed but is likely to be a problem for some species of bird (Fowler 1999) and fish. Certainly lugworm is an important prey item for the Grey Plover and the Bar-Tailed Godwits in the Severn (Goss-Custard et al. 1991), the former of which contributes to the 'internationally important assemblage of waterfowl' feature of the Severn Estuary Special Protection Area (SPA).

1.4 Legal protection and statutory obligations

The Severn Estuary is the largest coastal plain estuary in the UK and one of the largest estuaries in Europe. As such, it has a number of International and European conservation designations including Special Area of Conservation (SAC), Special Protection Area (SPA) and Ramsar site covering an area of 73,715.4ha. About one third of this area is composed of intertidal habitats including intertidal mudflats and sand flats, saltmarshes and rocky shores. Although *Arenicola marina* is not itself a protected species, the conservations status of a listed habitat automatically includes its typical species and will only be taken as 'favourable' if the status of its typical species is also favourable (Client Earth 2013). Additionally the EU Court of Justice has established that the concept of adversely affecting the integrity of a site should not be confined to Article 6(3) situations (potential plan or project in Natura 2000 sites) and will equally apply to Article 6(2) which is broader in scope and applies to the performance of all activities in SACs.

Arenicola marina is noted under a number of conservation objectives in the Natural England/ CCW Regulation 33 Advice for the Severn Estuary SAC and SPA. For the SAC *A.marina* is noted in three conservation objectives. The first two conservation objectives relate to SAC Feature 3 – intertidal mudflats and sandflats. Conservation objective C2 concerns the extent and variety of mudflat and sandflat communities comprising each sub-feature ('intertidal mud' and 'intertidal mud and sand'). The target for this conservation objective is 'no decrease in extent or range of types of intertidal mudflat and sandflat communities from an established baseline' (Natural England & the Countryside Council for Wales 2009). Conservation objective C4 covers the community composition of the features of which *A.marina* is a named species in the communities of two of the sub-features 'intertidal mud' and 'intertidal mud and sand'. The target for C4 is no decline in community quality due to changes in species composition or loss of typical species from an established baseline, subject to natural processes.

In the SPA mudflats and sand flats are named as a supporting habitat of interest feature 7- Internationally important assemblage of wildfowl. The conservation objectives for this interest feature and associated habitats include food availability where the target is no deviation in the presence and abundance of suitable prey species from an established baseline. *Arenicola marina* is one of the named prey species.

1.5 Aims and hypothesis

Whilst several papers on the invertebrate fauna of the Severn have included data on *Arenicola marina*, no detailed up-to-date baseline data exists to aid with management decisions for lugworm in the Severn Estuary SAC. The aim of this survey is to address this shortfall by collecting baseline data in the form of lugworm density estimates and basic population parameters for five intertidal mudflats and sand flats within the Severn SAC. There is also potential for this survey to be extended to a multi-year time series to look at natural fluctuations of lugworm populations so that future effects of large scale development (such as a barrage) or exploitation (from an increase in bait digging effort) can be discriminated from natural variability. As well as collecting baseline data we can begin to test a number of hypotheses pursuant to understanding the vulnerability of sandy beaches in the Severn SAC to external pressures:

1. *Arenicola marina* exhibits similar densities to other populations of intertidal lugworm
2. Separation of adults and juveniles occurs along a transect running from the upper to the lower shore, with juveniles found at the upper shore
3. The five beaches have relatively uniform distribution and densities of lugworm.
4. The proportion of adults and juveniles is similar across the beaches.
5. The lugworm populations of the five beaches are equally robust to exploitation.

2. Methodology

2.1 Site description

Five sandy beaches known to have relatively large populations of *Arenicola marina* as well being popular bait-digging locations were selected from within the Severn European Marine Site for D&S IFCA's baseline survey and on-going bait-density time series. The first three beaches, Burnham, Berrow and Brean form a continuous stretch of sand from the mouth of the River Parrett to Brean Down (*Figure 3*). Weston-Super-Mare and Sand Bay are both enclosed sandy bays (*Figure 3*). All have a 'long' beach profile with relatively similar substrates and profiles (Boyden and Little 1973). The upper sections of these beaches are sandy but further down these beaches change to thick mud (Boyden and Little 1973) however in some places there may be patches of sandier substrate within these larger muddy areas (pers.obs). The lever of siltation at Burnham appears to be most variable, with regular episodes of the entire sand area being covered in mud (per.obs.).

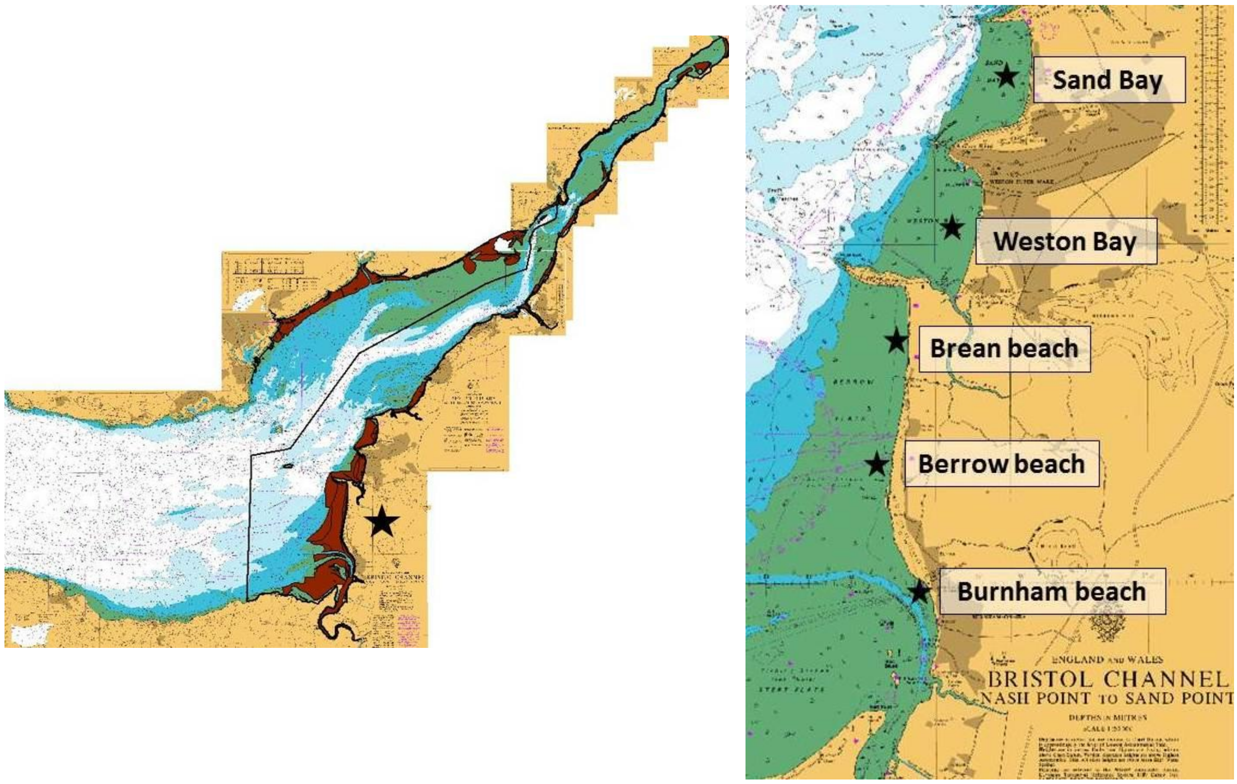

Figure 3. *a) The location of the beaches within the Severn Estuary European Marine Site and b) Sampling locations of lugworm densities within the Severn EMS*

2.2 Survey design

Transects were placed at regular 250m intervals along each beach. This interval was chosen to reflect the available resources and the amount of time the survey would take, relative to the window in which a suitable season and tides coincided. Starting at the top of the beach walking down the transect line the first quadrat was placed randomly within 5m of the transect line once the first lugworm had been sighted. The numbers of adult and juvenile lugworm within each of 9 subdivisions of a $1m^2$ quadrat were recorded. Although laboratory analysis is the most accurate method of determining adult and juvenile lug, this is extremely time-consuming as well as being a destructive sampling method. A quicker and non-destructive method of estimation is by measurement of the width of the faecal string of the lugworm (Zipperle & Reise 2005). Juveniles are generally classified as having a faecal string with a width of <2mm, whilst those of adults are ≥2mm (*Figure 4a*). A 2mm twine was used to subdivide the quadrat into a grid providing a very simple way of estimating the faecal string width (*Figure 4b*). After the first quadrat another was recorded approximately every 25m along the transect, placed randomly within 5m of the transect line. This continued until either the end of the lug bed was reached or the mud became too deep to continue into. The end of the transect was recorded and the reason for its completion was noted (i.e. unsafe conditions or absence of lug). The presence or absence of the small gastropod mollusc *Hydrobia ulvae* was also noted in every quadrat, as was a working description of the sediment type.

Figure 4. *The difference in size between adult and juvenile lugworm was often conspicuous and could be determined by eye with some confidence (a) or more intermediate sized casts could be compared to the thickness of the twine used to subdivide the $1m^2$ quadrat (b).*

2.3 Statistical analyses

Basic descriptive statistics (density measures and associated standard deviations) were carried out in Microsoft Excel. Total lug densities are based on pooling of adult and juvenile densities. Mean densities for each beach were based on pooling all quadrats from all transects. Maximum density was simply the highest number of lugworm found in any single quadrat on each beach.

Box and whisker plots were constructed using R v.3.0.0 to visualise total lug densities and juvenile lug densities within and between beaches. Statistical differences between beaches were assessed using Mann-Whitney U tests (also known as Wilcoxon's signed rank test). Mann-Whitney tests are a non-parametric equivalent of the traditional t-test used for assessing differences in means between two samples. Mann-Whitney tests were carried out for differences in total lug densities for all possible pairwise comparisons of beaches. Because the tests were carried out multiple times, there was an increased risk of Type II Error (where a significant difference is found purely by chance, when none exists in reality). Therefore a Bonferroni Correction was applied to reduce the acceptable p-value and correct for multiple tests. The Bonferroni correction simply takes the significance value (p=0.05) and divides it by the number of pairwise comparisons tested (N=10). Therefore a new p-value of 0.05/10 = **0.005** was used to test for significant differences between beaches. Identical pairwise comparisons were carried out for differences in juvenile lugworm densities between beaches, Bonferroni significance corrections were carried out as above.

Analysis of differences in adult and juvenile lugworm densities between beaches was carried out using PRIMER-E v.6.0. Similarities (or differences) were calculated based on untransformed adult and lugworm densities between all possible pairs of individual samples (quadrats) using the Bray-Curtis similarity index. Similarities are then ranked, forming a rank similarity matrix on which the following analyses were based. An analysis of similarities (ANOSIM) was carried out to test for differences in the relative densities of adult and juvenile lugworm on the upper and lower shore, to test for the presence of nursery beds. ANOSIM is a multivariate non-parametric permutation test, analogous to the ANOVA in univariate statistics but varies from the classical MANOVA test in its being based on a similarity matrix rather than actual sample numbers. This is a distinct advantage when working with biological species data which is inherently "0 rich" and unsuitable for traditional approaches (Clarke & Warwick 2001). Based on *a-priori* anecdotal information about the distribution of adult and juvenile lugworm, quadrats were assigned to one of two 'zones'. The first zone known as 'nursery bed' was made up of the upper three quadrats of a transect, covering the first 50m of the upper shore. All other quadrats were placed into the 'adult bed' zone. 999 permutations were carried out and resulting R-values and Significances are reported.

Based on the rank similarity matrix described above, a CLUSTER analysis was also undertaken in PRIMER-E v.6.0 in order to aid with visualisation and interpretation of the data. Cluster analysis aims to find natural groupings of samples so that samples within a group are more similar to each other than samples in different groups (Clarke and Warwick 2001). Primer-E utilises a technique called hierarchical agglomerative clustering resulting in a dendrogram with the y-axis defining a similarity at which two samples are considered to have 'fused' (Clarke and Warwick 2001). A SIMPROF test was conducted in tandem with the CLUSTER analysis which assigns a level of significance to clusters occurring within the CLUSTER analysis, with the significance level set at 5% for this study.

3. Results

3.1 Blow lug densities across the five sites

Mean densities of *Arenicola marina* measured at the five sites varied between 2.21 m^{-2} and 4.64 m^{-2} (*Table 2*) with an average across all the beaches of 3.89 m^{-2}. Pairwise comparisons of the beaches resulted in no statistical differences between beaches once multiple statistical tests had been corrected for by a Bonferroni correction (*Table 3*). This is perhaps unsurprising given the uniformly low densities of lugworm across the beaches. However, comparison of mean, median and maximum densities across the beaches may still reveal biologically significant patterns.

Table 2. *Mean densities (m^{-2}), standard deviations, and maximum densities (m^{-2}) of* Arenicola marina *across the sandy beaches of the Severn European Marine Site*

Location	**Mean**	**SD**
Burnham-on-Sea	2.21	±2.44
Berrow	2.86	±2.75
Brean	4.64	±5.47
Weston-Super-Mare	4.21	±6.41
Sand Bay	2.91	±4.20

Table 3. *Mann Whitney U-tests for statistical pairwise comparisons of mean lugworm densities between beaches. A Bonferroni correction results in statistical significance being set at P>0.005.*

	Burnham	Berrow	Brean	Weston-Super-Mare
Burnham	-	-	-	-
Berrow	0.1837	-	-	-
Brean	0.0094	0.0995		-
Weston-Super-Mare	0.8035	0.2925	0.1101	-
Sand Bay	0.8528	0.2044	0.0625	0.45

The box-and-whisker plot shows that the median lugworm density (thick black lines) increased from South to North lug with a peak at Brean before declining again towards Sand Bay (*Figure 5*) similarly to mean densities (*Table 2*). The exception to this is Weston-Super-Mare which had the second greatest mean density (*Table 2*) but the joint lowest median density (*Figure 5*). As can be seen in *Figure 5* Weston-Super-Mare has many samples with low lugworm density but is skewed to a higher mean by a small number of quadrats with high densities, suggesting greater patchiness at Weston-Super-Mare. Sand Bay shows a similar pattern with a much lower median than mean density, suggesting patchiness of individuals at this beach also. The maximum lugworm densities corresponded with the two beaches with the highest mean densities, Brean and Weston-Super-Mare both with a peak of $25m^{-2}$. Maximum density was lowest at the beach with the lowest overall mean density; Burnham on Sea, at $11m^{-2}$ (*Figure 5*).

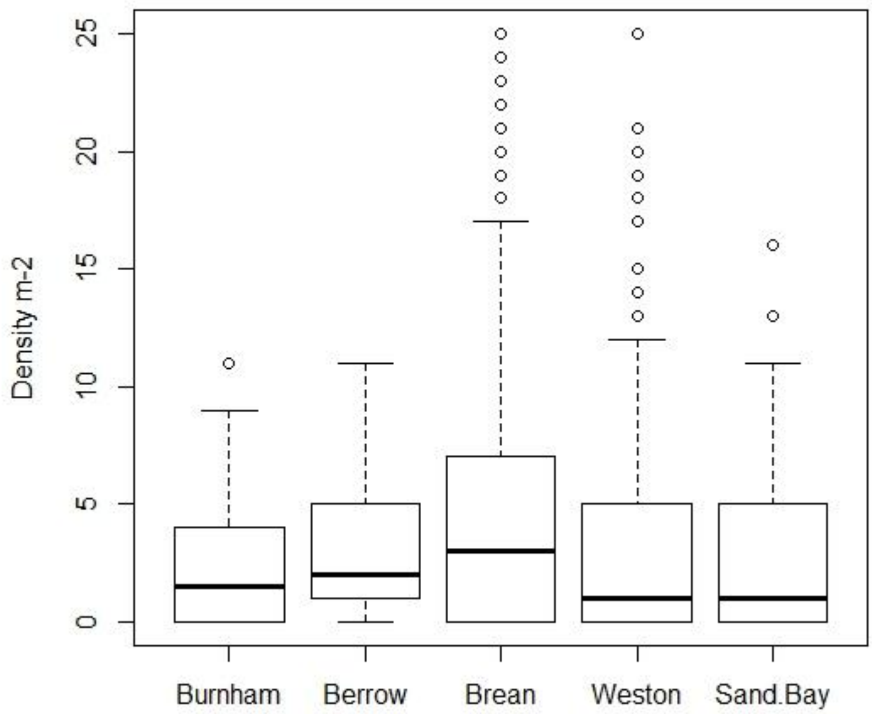

Figure 5. *Box and Whisker plots of the distribution of total l densities of* Arenicola marina *across the sandy beaches of the Severn Estuary SAC. Thick black lines denote median lugworm densities. The length of the box is the interquartile range. The vertical lines from the top of each box show the highest mean density which is within 1.5 interquartile ranges of the top. Similarly where applicable a vertical line shows the lowest mean density that is within 1.5 interquartile ranges of the bottom. All observations beyond this are plotted individually.*

3.2 Adult and juvenile distribution within beaches

At Burnham beach there is no increase in the mean density of juveniles relative to adults on the upper shore (*Figure 9*, Appendix A). At Burnham adults are rare and juveniles dominate (see following section) so that the pattern is almost the reverse of that expected – if anything juvenile density generally increases down the shore.

At Berrow some transects show the presence of juveniles higher up the shore with adults absent from these areas (*Figure 10*, Appendix A). However juvenile density is relatively constant with only one transect showing a peak towards the upper shore. Brean beach has been split into two images as it is the largest individual area of any of the beaches considered here. Lower Brean (Southern end; *Figure 11a*, Appendix A) shows a pattern of both differentiation and overlap between adult and juvenile populations. Towards the southern end there is no discernible pattern, but as you head North Juvenile lug do tend to peak towards the upper-mid shore, relative to adults which have a more constant density. At upper Brean beach (Northern end; *Figure 11b*, Appendix A) the southern half shows no pattern whilst the northern half shows a definite peak in juvenile density at the upper-mid shore, with no corresponding pattern in the adults. At Weston-Super-Mare (*Figure 12*, Appendix A) some locations do see an increase in juvenile lug density higher up the shore, but these are often mirrored by the adult lugworms which also show a similar increase in density higher up the shore. These patterns are most visible in the northern part of the beach. At Sand Bay there was no obvious band of juveniles on the upper shore or other pattern which shows differentiation in the distributions of adults and juveniles (*Figure 13*, Appendix A).

ANOSIM analysis revealed significant differences between adult and nursery beds at Berrow, Brean and Weston-Super-Mare, but not at Burnham or Sand Bay, when the density of adults and juveniles across all quadrats and transects were pooled for each beach and input as sample variables. By far the strongest differentiation was at Weston-Super-Mare with a relatively low R value of 0.318, which suggests that despite significant differences between the two bed types, much overlap still occurred (*Table 4*).

Table 4. *Results of ANOSIM analysis of differentiation between nursery beds and adult beds in terms of density of adult and juvenile blow lug.*

Beach	**R**	**p %**	**sig (p)**
Burnham	-0.016	82.50	Non significant
Berrow	0.149	1.2	P < 0.05
Brean	0.109	0.1	P < 0.005
Weston	0.318	0.1	P < 0.005
Sand Bay	0.059	21.4	Non significant

CLUSTER analysis for Weston-Super-Mare showed three major groupings with further significant subdivisions (*Figure 6*). The first group, all with 0% similarity are quadrats with no lug in them. The second major group with ~68% similarity contains all the quadrats with only adults, no juveniles. Interestingly, with the exception of one sample, all quadrats with ONLY adults fell into the *a-priori* designated Adult Bed category. The third group has approximately 25% similarity but is further subdivided into three statistically significant groups (SIMPROF p<0.05). The first of the three groups is defined by the fact that all samples have high numbers (7-16 m^{-2}) of juvenile lugworm. This is often, but not always associated with high adults densities as well. All of these samples fall into the *a-priori* designated Nursery Bed category. The next group contains samples which showed high numbers of adults and low numbers of juveniles, and is a mixture of Adult and Nursery Bed categories (i.e. samples that came from the first 50m of the shore and samples that came from below 50m). The final group is made up of samples that contained low numbers of juveniles, and occasional adults. The majority of samples in this group come from the 'Nursery Bed' category, with a few from the 'Adult Bed' category (*Figure 6*).

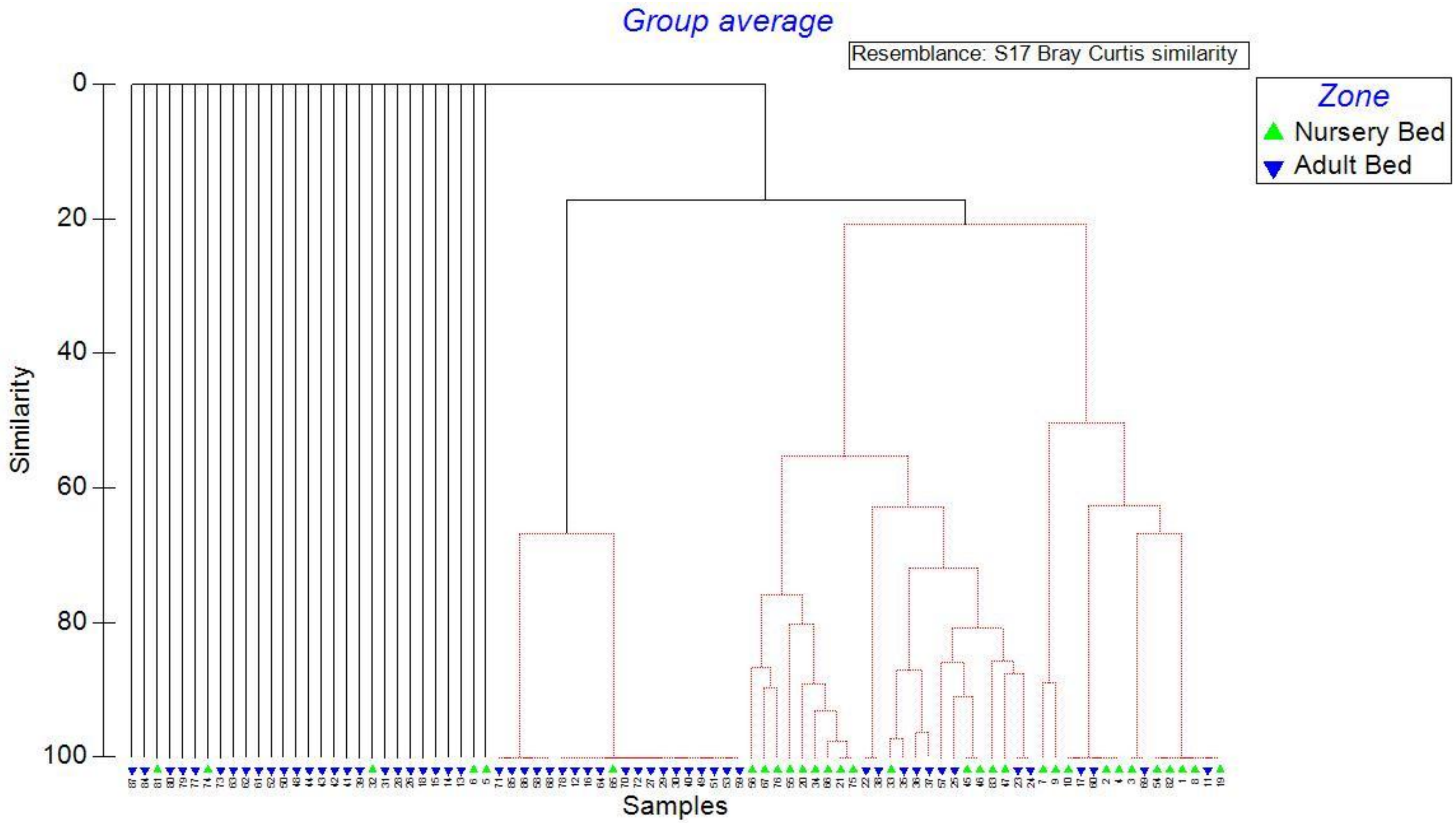

Figure 6. *Cluster diagram of similarity between quadrats in terms of adult and juvenile lugworm abundance. A SIMPROF analyses tested for significant differences between clusters. Significantly different clusters are shown in red. Quadrats are sorted by Zone to look at whether significant differences occur between in abundance of adults and juveniles in the proposed zones.*

3.3 Adult and juvenile distribution between beaches

Differences in the proportions of adults and juveniles occurred across the 5 sites. *Figure 7* shows that whilst over 90% of all lugworm casts reported at Burnham were juveniles, only 20% of casts were juveniles at Sand Bay. The proportion of adults and juveniles decreased in a stepwise manner in a northwards direction with Burnham having the highest percentage of juveniles and Sand bay having the lowest. The highest mean density of juveniles was found at Brean (*Table 5*). The lowest mean juvenile densities were found at Sand Bay. At Burnham, which had the lowest total lugworm mean density (*Table 2*, Section 3.2) conversely had the second highest mean juvenile density (*Table 5*) and the highest median juvenile density (Figure 8). Statistical pairwise comparisons between the beaches confirmed that the beach with the lowest proportion of juveniles (Burnham) had statistically different mean densities of juvenile lugworm to the two beaches with the highest proportion of adults; Weston-Super Mare and Sand Bay (*Table 6*). Differences in the mean density of juveniles were not statistically significant between any other pairwise beach comparisons (*Table 6*).

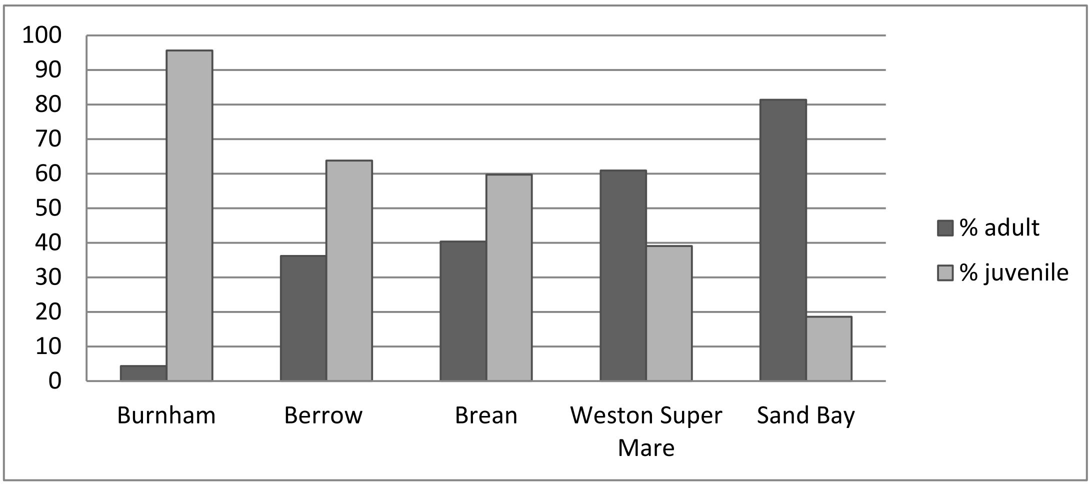

Figure 7. *The percentages of adult and juvenile lugworm across the five study sites in the Severn Estuary SAC.*

Table 5. *The mean density of juvenile* Arenicola marina *across the five study sites in the Severn Estuary SAC.*

Site	Mean Juvenile Density
Burnham	2.113
Berrow	1.809
Brean	2.77
Weston	1.644
Sand Bay	0.5429

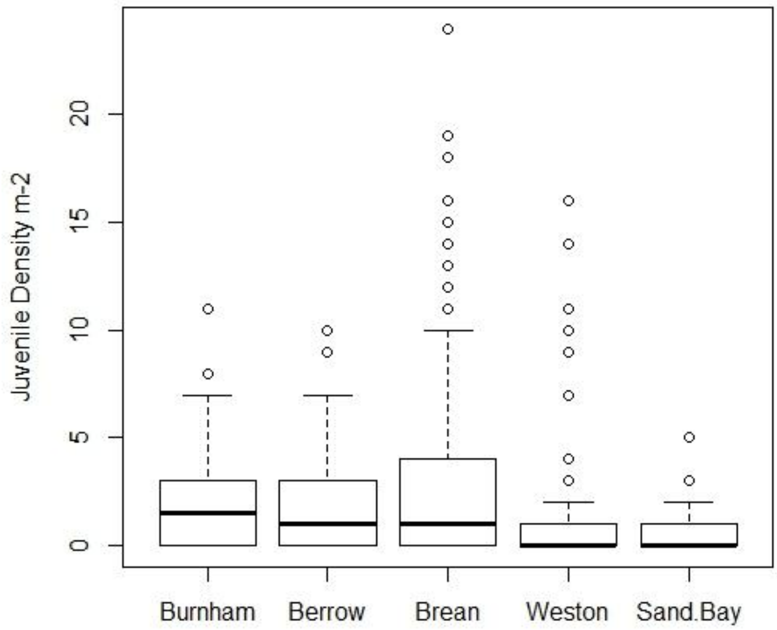

Figure 8. *Box and Whisker plots of the distribution of juvenile lugworm densities of* Arenicola marina *across the sandy beaches of the Severn Estuary SAC. Thick black lines denote median lugworm densities. The length of the box is the interquartile range. The vertical lines from the top of each box show the highest mean density which is within 1.5 interquartile ranges of the top. All observations beyond this are plotted individually.*

Table 6. *Mann Whitney U-tests for statistical pairwise comparisons of mean lugworm densities between beaches. A Bonferroni correction results in statistical significance being set at P > 0.005. Statistically significant results are highlighted and marked with *asterisk.*

	Burnham	Berrow	Brean	Weston-Super-Mare
Burnham	-	-	-	-
Berrow	0.3149	-	-	-
Brean	0.6317	0.0995		-
Weston-Super-Mare	**0.0024***	0.2925	0.1101	-
Sand Bay	**0.0002***	0.2044	0.0625	0.4500

4.0 Discussion

4.1 Densities of Blow lug in the Severn

The maximum densities of blow lug in the area of the Severn described by this study are within the range of those found in other estuaries in the UK (*Table 7*). Encouragingly, the results agree closely with lugworm densities reported by Boyden and Little (1973) for the Severn Estuary. Boyden and Little found a maximum density of *Arenicola marina* of ~23 m^{-2} at Brean which agrees very closely with the maximum reported by this study; 25 m^{-2} at both Brean and Weston-Super-Mare. However this study did find higher maximum lug densities at Sand Bay, Berrow and Weston-Super-Mare than those reported by Boyden and Little (1973). Both this study and Boyden & Little (1973) were carried out their fieldwork during the summer months (July-August) so it is unlikely that this accounts for the differences. However, Boyden and Little (1973) base their maximum lug densities from single transects at each beach. As lug densities were very patchy, it is possible that they may have underestimated the maximum lug densities at some of the beaches. Alternatively, there could have been a genuine increase in maximum lug density in the 40 years since Boyden and Little's study took place (1972) to the present study (2012-2013). It is notable that despite the 40 year gap, the spatial pattern of maximum density between beaches agrees very closely with the results of this study. Whilst Boyden and Little (1973) did not sample Burnham, they found Berrow to have the lowest maximum density, followed by Sand Bay, then Weston-Super-Mare and Brean, agreeing completely with our own findings. Boyden and Little (1973) also extend their search area, sampling a total of 17 beaches in the Severn, finding a peak in maximum density of blow lug at Minehead of 49 m^{-2}.

Table 7. *A comparison of maximum density of* A.marina *in estuaries across the UK, adapted from Boyden and Little 1973*

Estuary	**Maximum density of *Arenicola marina* (m^{-2})**	**Reference**
Severn(Sand Bay & Brean)	25	This study
Severn(Minehead)	49	Boyden and Little 1993
Tamar	3	Spooner and Moore 1940
Exe	136	Holme 1949
Dovey	11	Beanland 1940
Dee	16	Stopford 1951

Mean densities of *Arenicola marina* in the Severn are relatively low compared to other locations in which it has been recorded (*Table 8*). In Budle Bay, Northumberland, mean lugworm densities varied between 30.3 and 46.4m^{-2} (Olive 1993) relative to 2.5 and 5.2m^{-2} recorded in this study. On Balgzand (the Netherlands) late-winter densities over a 24 year annual time series were all within the range 14-36m^{-2}. However it may be that the coasts of the North Sea support particularly high lugworm densities. Various studies of the Welsh coast have shown lugworm densities more similar to those found in the Severn. At the control sites of an experimental bait-digging survey on two sheltered beaches in South Wales *A.marina* mean densities varied

Table 8. *A selected comparison of mean recorded densities of lugworm from this study to those reported in the published literature.*

Location	Species	Habitat	Sampling method	Mean density (ind. per m^2)	Reference
UK Severn Estuary	*Arenicola marina*	Intertidal muddy sand flats	Faecal cast counts without a correction factor	**2.2 – 4.6**	This study
UK, Severn Estuary	*Arenicola marina*	Intertidal muddy sand flats	Faecal cast counts with no correction factor	**3.89**	Boyden and Little 1973
UK, South Wales, Barry Harbour	*Arenicola marina*	Sheltered beach	Time series of control areas for digging experiment	**1.89 - 8.77**	Cryer et al. 1987
UK, South Wales, West Aberthaw	*Arenicola marina*	Exposed beach	Time series of control areas for digging experiment	**2.39 - 17.53**	Cryer et al. 1987
UK, South Wales, Swansea Bay	*Arenicola marina*	Sheltered beach	Time series of control areas for digging experiment	**0.74 - 3.75**	Cryer et al. 1987
UK, Northumberland Budle Bay	*Arenicola marina*	Intertidal muddy sand flats	Counting casts	**30.3 - 46.4**	Olive 1993
UK, Northumberland Fenham Flats	*Arenicola marina*	Intertidal muddy sand flats	Counting casts	**23 - 28**	Olive 1993
New Zealand	*Abarenicola affinis*	Tidal inlets	Faecal cast counts with a correction factor of 1.09	**11.1**	Görlitz 2012
Southern Chile	*Abarenicola affinis*	Shallow hypoxic subtidal with fine sand and silt-clay sediments	Van Veen Grab	**134**	Moreno et al. 2007
Balgzand, Netherlands	*Arenicola marina*	Intertidal mudflats	(over 24 annual time series)	**14 - 36**	

temporally between 0.74-3.75m^{-2} and 1.89-8.77m^{-2} (Cryer et al. 1987). As part of the same study mean densities reached 2.39-17.53m^{-2} at an exposed beach in West Aberthaw (Cryer et al. 1987) (*Table 8*). Alternatively, the estuarine environment of the Severn may reduce the densities of lugworm in the Severn compared to other locations. Again, the nature of the sediment in the Severn appears to be the likeliest factor resulting in lug densities towards the lower end of those seen in Northern Europe, but factors on larger geographic scales may also be operating.

Boyden and Little (1973) suggest that at its most landward extreme (Sharpness) the distribution of *A.marina* is probably limited by the salinity tolerances of juveniles. Elsewhere in the Severn they speculate that the distribution of lugworm is probably limited by the existence of suitable habitat. They do not expand on what 'suitable habitat' might be, but suggest that blow lug prefer 'muddy sand'. A detailed study into the distribution of *A.marina* in relation to particle size and organic content of sediments along the north Kent coast looked at this question more closely (Longbottom 1970). The study found that *A.marina* was not found on beaches with extremely fine sediments i.e. with deposits of median particle size less than 80µ, probably because individual worms cannot maintain their burrows. In beaches with very coarse sediments i.e. a median particle size of more than 200µ Longbottom (1970) also failed to find any lugworm. On beaches which were gently sloping and moderately well drained with median particle sizes between the two aforementioned extremes then lugworm biomass varied logarithmically with particle size, with smaller particle sizes having a greater lugworm biomass. The median particle size also correlated extremely well with the amount of organic matter available. Therefore Longbottom (1970) surmised that lugworm biomass was controlled by the amount of food available, which in turn correlated with the median particle size. In the Severn it seems unlikely that there would be a strong cline in food availability over such a short distance, although it is possible that differences in sediment grain size may vary, so that the availability of suitable food may vary between beaches. Sediments in the Severn are particularly fine, even when compared to other estuaries in South West England (Warwick et al. 2001). It is therefore possible that the existence of sediment with particle size >80µ is limiting in the Severn and the distribution of sand relative to mud on the beaches may be causing differences in lug density between the beaches. However at this time, this is entirely speculative and requires further investigation.

4.2 The distribution of adults and juveniles within and among the sandy beaches of the Severn

Much research now suggests that the adult and juvenile lugworm are not homogenously distributed along a transect running from the upper to lower shore on tidal flats (Farke et al. 1979, Pollack 1979). Instead, the near-shore areas are thought to be particularly important for juvenile lug with adults occurring further seaward (Farke 1979). Two types of 'nursery bed' have been described in the past. The first is where adults and juveniles occur in mixed populations, with juveniles more numerous on the upper shore (Thamdrup 1935); the second is where juvenile worms settle predominantly in near-shore areas (Wohlenberg 1937). The along-transect distribution of adult and juvenile lugworm varies significantly between the beaches of the Severn. At Weston-Super-Mare there is evidence for differentiation between adult and juvenile populations only at the northern end of the beach.

Differentiation of adult and juvenile lugworms also occurred to a lesser degree at Brean and Berrow. The general pattern in the Severn, where differentiation does occur, is of the type described by Thamdrup (1935), with high numbers of adults and juveniles found high on the shore, rather than exclusively juveniles, and relatively fewer juveniles further down the shore. However in many places in the Severn, this does not occur with distributions of adults and juveniles being relatively randomly distributed along the transects. The lack of clear spatial structure between adult and juvenile lugworm may be due to the patchy and dynamic mud environment found at many of the sampling sites, but may also be related to the relative abundance of adults and juveniles between beaches.

The most marked, and unanticipated difference in pattern in the distribution of adult and juvenile lugworm was therefore not that within beaches, instead it is between beaches. Whilst many previous studies compare overall densities across several beaches (Longbottom 1970, Boyden and Little 1973, Cryer et al. 1987), very little data exists as to ratios or proportions of adults to juveniles across a geographical area. One possible explanation for the extremely low proportion of adults at Burnham-on-Sea might be related to the sporadic covering of sandy areas of Burnham beach by muddy deposits (pers.obs). This may cause a local extinction of any lugworm which are living there. As only juvenile lugworm are thought to migrate long distances (Flach and Beukema 1994), it seems more likely that any recolonisation will be by juvenile lugworm. Additionally, Longbottom (1970) found that the only *A.marina* found in fine deposits were juvenile worms which form very shallow burrows. However, no similar processes are known which would form the gradient in the proportion of juvenile lugworm from Burnham to Sand Bay. A gradient in salinity which negatively affects juvenile lug worm is unlikely to be the mechanism, as lugworm are recorded as far north as Sharpness, and further seaward salinity is not thought to be limiting factor for *A.marina* (Boyden and Little 1973). A gradient in median sediment grain size across the beaches may be affecting the relative proportions of adult and juvenile lugworm across the five beaches, but data of sufficient detail to be relevant to this study are not available. One complicating factor in the comparison across the beaches is the fact that Burnham, Berrow and Brean beaches were surveyed in 2012, whilst Weston-Super-Mare and Sand Bay were surveyed in 2013. In other tidal flat systems, numbers are known to be relatively stable through time (Flach and Beukema 1994). However, whether this is the case in the Severn is unclear and so cannot be ruled out as a confounding factor. Finally, the total amount and distribution of sand and mud sediments of various size, as well as water and organic content of those sediments, varies greatly across the five beaches. Although the overall pattern (sand leading to thick mud) is similar across the beaches, the distribution of intermediate sediments may differ between beaches and affect the distribution of adult and juvenile lug, spatially and possibly temporally.

Finally, this study has only considered the distribution of lug above the low tide mark. As juvenile lugworms are thought to overwinter in subtidal channels before colonising the upper (or lower!) shore, knowledge of the subtidal distribution of suitable habitat and lugworm may help inform current knowledge on the distribution of lugworm throughout the Severn Estuary EMS.

5.0 Conclusions and Future Work

5.1 Management implications

The results show that the five beaches are quite different in terms of their mean and maximum density, adult and juvenile distributions and adult-to-juvenile ratios of *Arenicola marina.* However, the similarity between the results of this study and mean and maximum densities recorded by Boyden and Little (1973) suggest that lugworm populations in the Severn are relatively stable. Additionally, the close proximity of nearby populations should mean that exploited populations will be easily recolonised despite the overall low density of lugworm in the Severn relative to other areas in the UK and Northern Europe. Therefore the current level of bait digging effort, of which the vast majority is for personal use by local sea anglers, is thought to be sustainable. Long-term monitoring of both bait populations and bait-digging effort is required to confirm this baseline data.

5.2 Future work

The data for this study was collected over two years, with Burnham, Berrow and Brean being sampled in 2012 and Weston-Super-Mare and Sand Bay being sampled in 2013. Whilst the patterns between individual beaches agrees with results from 1972 (Boyden & Little 1973), it would be preferable to have all the results from the Severn collected in the same year to prevent confounding between-year differences affecting the perceived spatial pattern. The aim for future lugworm density surveys will therefore be to survey all 5 beaches within a summer. A long-term sampling regime monitoring the densities of lugworms across the beaches will provide a better understanding of population dynamics both within and between beaches as well as provide more robust baseline data for any future increases in bait digging activity.

6.0 Acknowledgments

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Appendix A

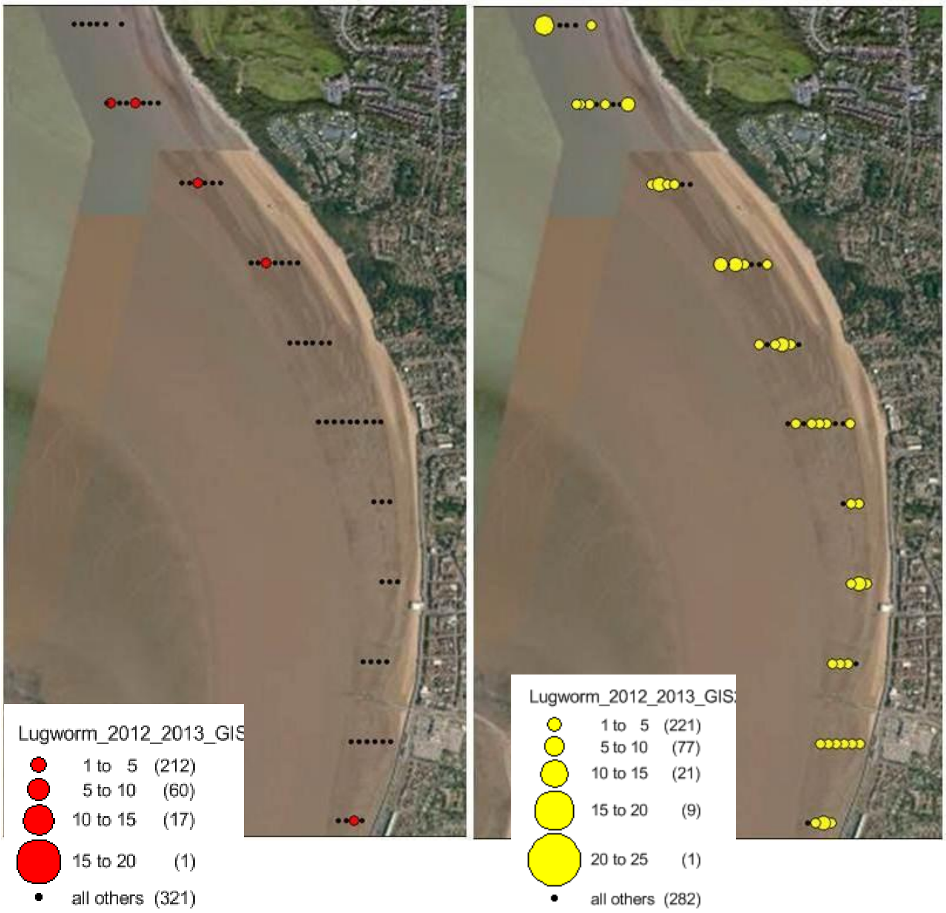

Figure 9. *The distribution of adult lug worm density (red circles) and juvenile lug worm density (yellow circles) along and across the shore at Burnham Beach, Somerset.*

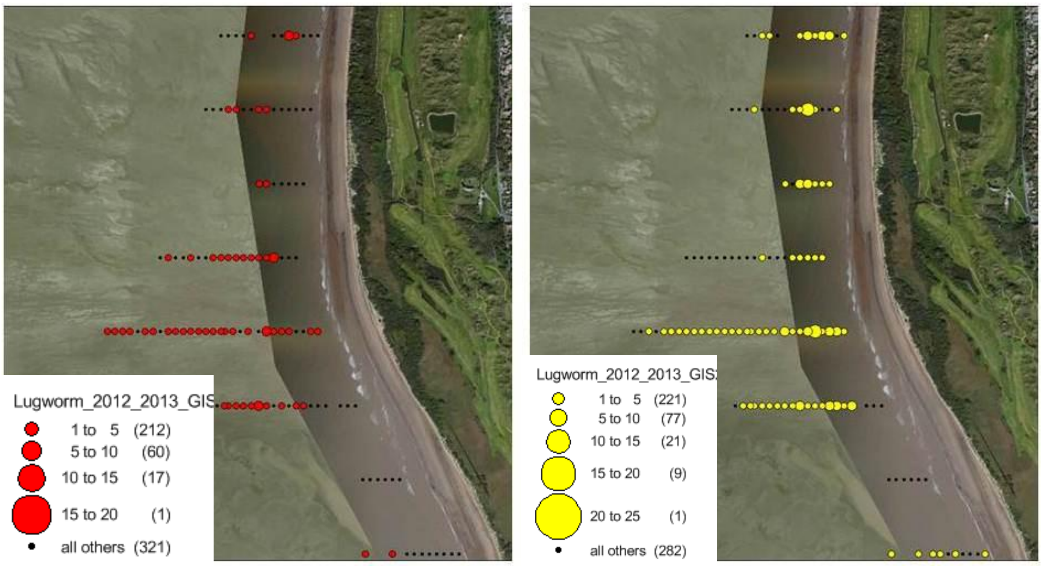

Figure 10. *The distribution of adult lug worm density (red circles) and juvenile lug worm density (yellow circles) along and across the shore at Berrow Beach, Somerset.*

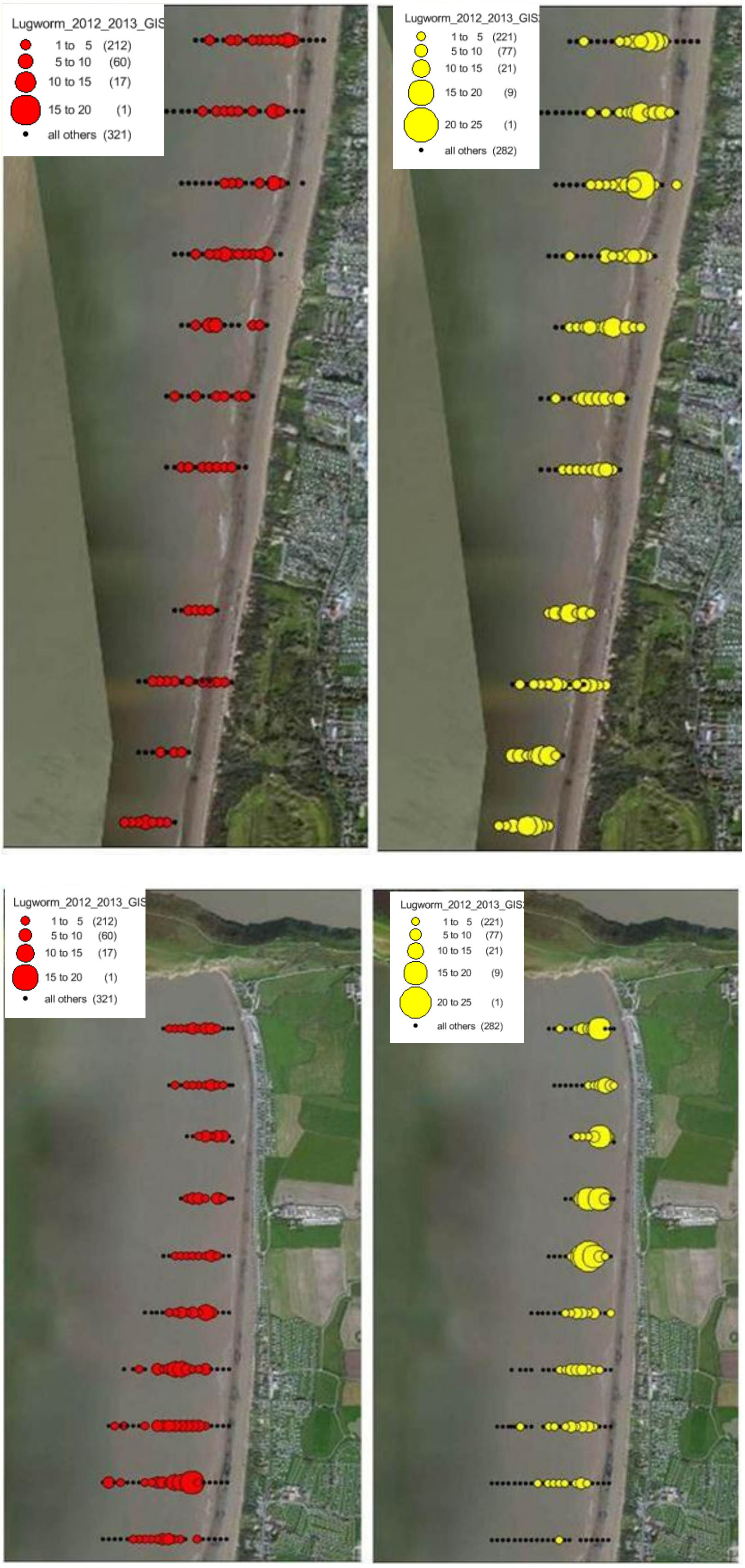

Figure 11. *The distribution of adult lug worm density (red circles) and juvenile lug worm density (yellow ircles) along and across the shore at lower (a) and upper (b) Brean Beach, Somerset*

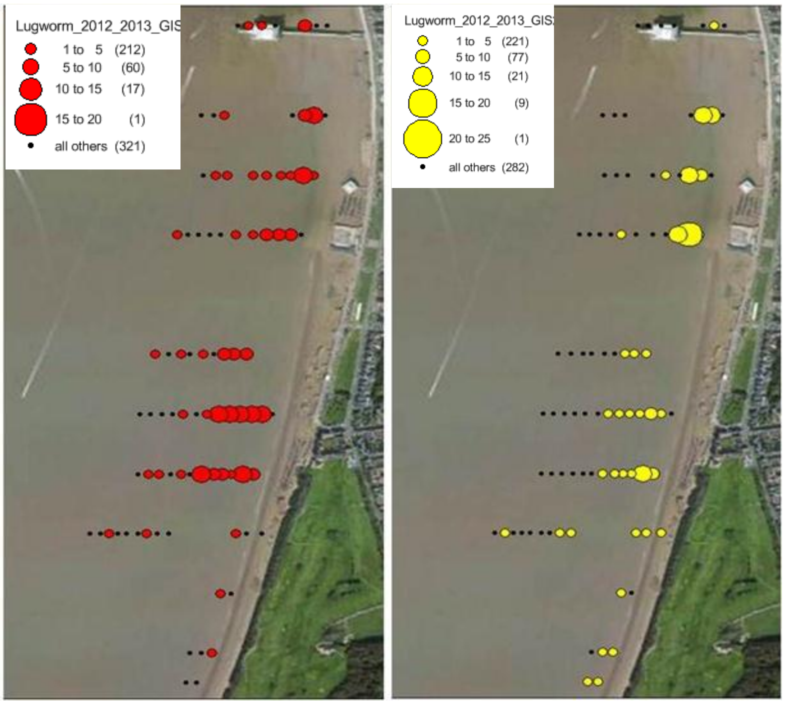

Figure 12. *The distribution of adult lug worm density (red circles) and juvenile lug worm density (yellow circles) along and across the shore at Weston-Super-Mare Beach, North Somerset.*

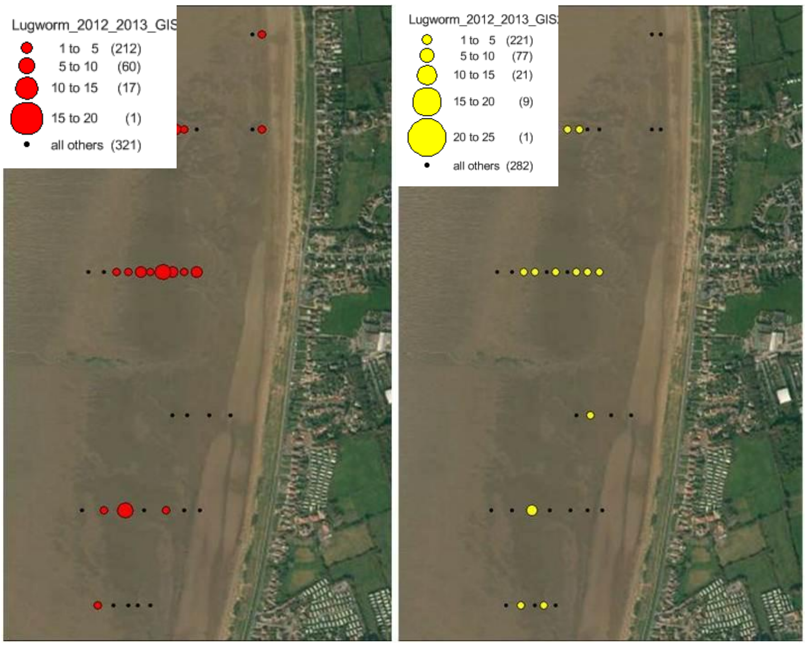

Figure 13. *The distribution of adult lug worm density (red circles) and juvenile lug worm density (yellow circles) along and across the shore at Sand Bay, North Somerset.*