The abundance, movement and population characteristics of common whelk, *Buccinum undatum* (L.), in an area under consideration for an offshore windfarm development in the territorial waters of the Isle of Man.

A thesis submitted in partial fulfilment of the requirements for the degree of Master of Science (M.Sc.) in Marine Environmental Protection

Bangor University 2016

In collaboration with:

**Fisheries & Conservation Science Group**

Edward Bolger  
B.Sc. Natural Sciences (2014, Durham University)  
School of Ocean Sciences, Bangor University, Menai Bridge, Anglesey, LL59 5EY, UK  
www.bangor.ac.uk  
edbolger1@gmail.com  
Submitted in September, 2016
This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any degree.

Signed  
Date 15/09/16

This thesis is the result of my own investigations, except where otherwise stated. Other sources are acknowledged by footnotes giving explicit references. A bibliography is appended.

Signed  
Date 15/09/16

I hereby give consent for my thesis, if accepted, to be available for photocopying and for inter-library loan, and for the title and summary to be made available to outside organisations.

Signed  
Date 15/09/16
Acknowledgements

I would like to thank Professor Michel Kaiser, Dr Isobel Bloor and Jack Emmerson M.Sc. for their expertise, support and guidance throughout the duration of this project. I would also like to thank Jon Jo Skillen, skipper of ‘Boy Shayne’, and Jordan Corkill without whom this project would not have been possible. Thank you to the Department of Environment, Food and Agriculture for their generous provision of facilities and use of the FPV Barrule. Thanks also go to Chyanna Allison, Nicola Dempster and Zachary Radford, whose assistance with the creation and application of the rubber band tags was greatly appreciated.
Abstract

The abundance, movement and population characteristics of commercially exploited common whelk, *Buccinum undatum* (L.), were investigated in an area under consideration for an offshore windfarm development in the territorial waters of the Isle of Man, from June – July 2016. A Lincoln-Peterson mark-recapture survey, using tags with unique identification codes, to estimate abundance and movement, was carried out in 3 x 1km² sample areas within the windfarm area. In total, 2722 *B. undatum* were tagged and released. Recapture rates were variable, with an overall recapture rate of 1.62%. The mark-recapture survey produced a population abundance estimate of 0.20 individuals m⁻² and an average movement speed of 9.13 m day⁻¹. Based on the abundance estimate produced, the value of the *B. undatum* stock in the windfarm area, June – July 2016, was approximately £3.99 million (not taking into account replenishment of the stock over time). Catch Per Unit Effort (CPUE) was estimated in the windfarm area and tested for differences between ‘stand-up’ and ‘lay-down’ pot designs. Mean CPUE was 2.94 kg pot⁻¹, with no significant difference between pot types. 84 *B. undatum* sampled from the windfarm area were analysed in the laboratory to produce Total Shell Length (TSL) distributions, size at maturity and length-weight relationships. TSL in the windfarm area ranged from 54.7 - 124.0 mm with only 1.27% of individuals under the minimum landing size of 70mm. Size at maturity varied between sexes, at 69.8 mm TSL for females and 83.8 mm TSL for males. Length-weight relationships also varied between the sexes, with females displaying negative allometric growth and males displaying positive allometric growth.
Table of Contents

1. Introduction ................................................................................................................................. 1
   1.1 Biology .................................................................................................................................. 2
      1.1.1 Feeding and nutrition ................................................................................................. 2
      1.1.2 Growth ......................................................................................................................... 2
      1.1.3 Reproduction .............................................................................................................. 2
   1.2 *Buccinum undatum* (L.) fisheries ....................................................................................... 3
      1.2.1 Fishing methodology .................................................................................................... 3
      1.2.2 Relevance of *Buccinum undatum* (L.) fisheries ....................................................... 4
      1.2.3 *Buccinum undatum* (L.) fisheries in the Isle of Man ............................................... 5
      1.2.4 Mark-recapture studies of *Buccinum undatum* (L.) ............................................... 6
   1.3 Aim ......................................................................................................................................... 7
   1.4 Hypotheses ............................................................................................................................ 7

2. Methodology .................................................................................................................................. 8
   2.1 Survey area ........................................................................................................................... 8
   2.2 Fishing vessels .................................................................................................................... 9
   2.3 Fishing gear .......................................................................................................................... 9
   2.4 Mark-recapture survey ......................................................................................................... 10
      2.4.1 Tag design ..................................................................................................................... 10
      2.4.2 Tagging and release phase ......................................................................................... 11
      2.4.3 Recapture phase .......................................................................................................... 12
   2.5 Laboratory dissection analysis ............................................................................................ 13

3. Data analysis ................................................................................................................................. 14
   3.1 Mark-recapture analyses ...................................................................................................... 14
      3.1.1 Catch per unit effort (CPUE) .................................................................................... 14
      3.1.2 Pot type ....................................................................................................................... 14
      3.1.3 Movement ................................................................................................................... 15
      3.1.4 Lincoln-Peterson Index .............................................................................................. 15
      3.1.5 Population density ..................................................................................................... 16
      3.1.6 Valuation of the windfarm area for lease ................................................................. 16
   3.2 Laboratory dissection analyses ............................................................................................ 17
      3.2.1 Sexual maturity ........................................................................................................... 17
      3.2.2 Length-weight relationship ....................................................................................... 18
3.2.3 Total shell length distribution.................................................. 18

4. Results.......................................................................................... 19

4.1 Mark-recapture analyses............................................................. 19

4.1.1 Catch Per Unit Effort (CPUE): June – July 2016...................... 19

4.1.2 Pot type.................................................................................. 19

4.1.3 Lincoln-Peterson index............................................................ 20

4.1.4 Movement............................................................................. 22

4.1.5 Valuation of the windfarm area for lease............................... 22

4.2 Laboratory dissection analyses.................................................... 25

4.2.1 Total shell length distribution................................................ 25

4.2.2 Sexual Maturity..................................................................... 26

4.2.3 Length-weight relationship.................................................... 27

5. Discussion..................................................................................... 29

5.1 Mark-recapture analyses............................................................. 29

5.1.1 Catch Per Unit Effort (CPUE)................................................ 29

5.1.2 Mark-recapture to estimate abundance................................. 30

5.1.3 Recapture rate...................................................................... 32

5.1.4 Abundance.......................................................................... 32

5.1.5 Movement.......................................................................... 34

5.1.6 Valuation of the windfarm area for lease............................... 34

5.2 Laboratory analyses.................................................................... 35

5.2.1 Total shell length distribution................................................ 35

5.2.2 Maturity.............................................................................. 36

5.2.3 Length-weight relationship.................................................... 37

5.3 Recommendations for future methodologies............................. 38

5.3.1 CPUE Depletion.................................................................. 38

5.3.2 Modification of current Lincoln-Peterson methodology........ 39

5.3.2.1 Use of the desired coefficient of variation to determine

    appropriate sizes of sample areas.............................................. 39

5.3.2.2 Separate studies of movement and abundance................... 41

6. References.................................................................................... 43

6.1 Grey literature........................................................................... 50
List of Figures

**Fig. 1.** The common whelk *Buccinum undatum* (L.) captured using baited pots off the coast of Sussex, England. Image source: Lawler & Vause, 2009

**Fig. 2.** Female *Buccinum undatum* (L.) laying a mass of egg capsules, England. Image source: Lawler, 2013

**Fig. 3.** The annual landings (by weight) of *Buccinum undatum* (L.) (10^3 tonnes) in UK waters by UK vessels, from 2005 to 2014. Data sourced from MMO, 2016

**Fig 4.** Map of the Isle of Man, Britain, showing the offshore windfarm Agreement for Lease site, within which 3 x 1km^2 sample boxes were fished for *Buccinum undatum* (L.) during the mark-recapture study, from 14th June – 24th July 2016. Precise locations of the sample boxes are not shown to protect the commercial interests of the fishers involved.

**Fig. 5.** The commercial fishing vessel ‘Boy Shayne’ used for the recapture phase of the mark-recapture survey of *Buccinum undatum* (L.) in the offshore windfarm Area for Lease, east of the Isle of Man, from 23rd June to 24th July 2016.

**Fig. 6.** Photographs of typical A) Stand up pots and B) Lay down pot used for the capture of *Buccinum undatum* (L.). Image source: FAFB, 2016

**Fig. 7.** Photographs of A) The assembled tag, consisting of a lobster claw band, unique identification number on embossing tape and plastic snap-lock fastener B) *Buccinum undatum* (L.) with tag attached on board the FPV Barrule.

**Fig. 8.** Photograph showing the orientation of the *Buccinum undatum* (L.) shell when using Vernier callipers to measure total shell length (mm)

**Fig. 9.** The mean (±95% CI) daily CPUE of *Buccinum undatum* (L.) in kg pot^−1 landed in the windfarm Area for Lease (AfL), east of the Isle of Man, from 23rd June to 24th July 2016. No confidence interval was produced for 24/07/2016, as only a single string within the windfarm AfL was fished.

**Fig. 10.** Comparison of the mean (±95% CI) CPUE of *Buccinum undatum* (L.) in kg pot^−1 between stand-up and lay-down pot types. Pots were landed in the windfarm Area for Lease, east of the Isle of Man, from 23rd June to 24th July 2016.
Fig. 11. Lincoln-Petersen abundance estimates (±95% CI) for *Buccinum undatum* (L.) in survey areas B and C, located in the windfarm area for lease, east of the Isle of Man. Recapture period: 23rd June – 24th July.

Fig. 12. Density estimates (±95% CI) for *Buccinum undatum* (L.) in survey areas B and C, located in the windfarm area for lease, east of the Isle of Man. Recapture period: 23rd June – 24th July.

Fig. 13. All release and recapture locations for *Buccinum undatum* (L.) during the Lincoln-Petersen surveys in areas A, B and C, located in the windfarm area for lease, east of the Isle of Man. Recapture period: 23rd June – 24th July. More precise locations of recapture were produced for study areas A and B, as the pot number of recaptures was recorded. Pot number was not recorded for study area C so recapture points are defined as midpoints of the string. 3 additional strings were fished in study area C after the initial recapture session on 12th, 14th and 24th July. R = number of *B. undatum* recaptured.

Fig. 14. Release and recapture locations of recaptured *Buccinum undatum* (L.) during the Lincoln-Petersen surveys in areas A, B and C, located in the windfarm area for lease, east of the Isle of Man. Recapture period: 23rd June – 24th July. Lines indicate the shortest direct path between corresponding release and recapture points. More precise locations of recapture were produced for study areas A and B, as the pot number of recaptures was recorded. Pot number was not recorded for study area C so recapture points are defined as midpoints of the string. R = number of *B. undatum* recaptured.

Fig. 15. Box and violin plots of total shell length (mm) distributions for *Buccinum undatum* (L.) sampled from the windfarm area for lease (2016) and Ramsey Bay (Robinson, 2015) east of the Isle of Man. Increased width of violin plots indicates increased density of values. Horizontal line indicates the MLS of *B. undatum* in the Isle of Man (70 mm). n = sample size.

Fig. 16. Maturity ogive of model fit for male and female *Buccinum undatum* (L.) sampled from the windfarm area for lease, east of the Isle of Man, on 14th June 2016. The horizontal red lines indicate the proportion at which 50% of the sampled *B. undatum* were sexually mature. Length at 50% maturity is displayed in the bottom right corner of each figure.

Fig. 17. Inflection point indicating an allometric growth pattern based on variance between iterative tests on linear models of penis length (mm) and total shell length (mm) for male *Buccinum undatum* (L.). The dotted black vertical line is the value with the lowest mean standard error (83.9 mm TSL). The dotted red line is the minimum landing size for *B. undatum* on the Isle of Man. Maturity stage, based on visual examination of the gonad, is indicated by the colour of the point. *B. undatum* were sampled from the windfarm area for lease, east of the Isle of Man, on 14th July 2016.

Fig. 18. Length-weight relationships for female and male *Buccinum undatum* (L.) sampled from the windfarm area for lease, east of the Isle of Man on 14th July 2016. Calculated values for the parameters of the length-weight function are displayed. W = weight (g), L = total length (cm).
List of Tables

Table 1. The number and type of pots used in the mark-recapture study of *Buccinum undatum* (L.) in the offshore windfarm Area for Lease, east of the Isle of Man, from 23rd June to 24th July 2016.

Table 2. The total number of marked *Buccinum undatum* (L.) released in each 1km² study area during the release phase of the Lincoln-Petersen mark-recapture study in the Area for Lease offshore windfarm area, east of the Isle of Man, from 14th – 23rd June 2016.

Table 3. Methodology for the visual assessment of male and female *Buccinum undatum* (L.) maturity stage.

Table 4. The total number of *Buccinum undatum* (L.) counted in 10 full whelk sacks after landing. The mean value of the number of individuals per full sack was used to calculate the total number of unmarked *B. undatum* caught in the recapture phase of the Lincoln-Petersen surveys in areas A, B and C, located in the windfarm area for lease, east of the Isle of Man.

Table 5. The Lincoln-Petersen estimates of the population abundance and density of *Buccinum undatum* (L.) in survey areas A, B and C, located in the windfarm area for lease, east of the Isle of Man. Recapture period: 23rd June – 24th July.

Table 6. The mean (±95% CI) movement speeds of *Buccinum undatum* (L.) in survey areas A, B and C, located in the windfarm area for lease, east of the Isle of Man. Recapture period: 23rd June – 24th July.

Table 7. Results from published literature for mean recapture rates of tagged *Buccinum undatum* (L.) in Lincoln-Peterson mark-recapture studies. Recapture rate is expressed as a percentage of the total marked individuals that are recaptured.

Table 8. Results from published literature for densities (m⁻²) of *Buccinum undatum* (L.) with a range of locations and methodologies.

Table 9. Results from published literature for minimum landing size (MLS) and size at maturity (SAM) of *Buccinum undatum* using a range of methods and sampling months.
1. Introduction

The common whelk (*Buccinum undatum* L.) is a neogastropod mollusc, commonly distributed in coastal shelf waters in the east and west of the North Atlantic (Thomas and Himmelman, 1988; Valentinsson *et al.*, 1999; de Vooys & van der Meer, 2010) and the Arctic Oceans (Taylor & Taylor, 1977). *B. undatum* resides most commonly in depths from the subtidal zone to 200m (Thomas and Himmelman, 1988), although there are reports of *B. undatum* living at depths of up to 1200m in British waters (Ager, 2008). It is found on both hard and soft substratum types (Jalbert *et al.*, 1989).

*B. undatum* is a commercially exploited species, forming an important part of the shellfish fisheries of a number of countries surrounding the northern Atlantic, including Belgium, Iceland, Ireland, the Isle of Man, France and the UK (Nasution and Roberts, 2004). During the 1990’s, demand for *B. undatum* in South-East Asia, particularly Japan and South Korea, rose rapidly. This resulted in an expansion of the *B. undatum* fishery in the North Atlantic (Fahy *et al*., 2003). *B. undatum* exhibits a number of ‘K-selected’ life history traits, including low fecundity, long sexual maturation times and a long life span (Martel *et al*., 1986; Morrel & Bossy, 2004). The dispersal range of juvenile *B. undatum* is limited due to the lack of a planktonic larval stage and adult movement speeds are also limited to previously reported averages of 10 - 15m day\(^{-1}\) (Robson, 2014; Robinson, 2015). This limited dispersal, combined with the described K-selected traits, can result in localised populations of *B. undatum* that may be vulnerable to overfishing, as demonstrated by extinction events in the Wadden See (Morel & Bossy, 2004).

![Fig. 1. The common whelk *Buccinum undatum* (L.) captured using baited pots off the coast of Sussex, England. Image source: Lawler & Vause, 2009](image-url)
1.1 Biology

1.1.1 Feeding and nutrition

*B. undatum* uses chemoreception as a means of locating food sources (Bailey & Laverack, 1996; Mackie *et al*., 1968; Nielsen, 1974). Seawater is inhaled through an anterior siphon, at the base of which is a chemosensory organ, the osphradium (Nielsen, 1974). *B. undatum* is both an active predator and an opportunistic carrion scavenger. Stomach content analysis shows that *B. undatum* prey items include polychaetes, sipunculid worms, crustacea, small echinoderms and bivalves (Blegvad, 1915; Hancock, 1960; Nielsen, 1974; Taylor, 1978). *B. undatum* is also a scavenger and will feed upon moribund and dead animals (Blegvad, 1915; Hunt, 1925; Nielsen, 1974). *B. undatum* has selective preferences for carrion, with swimming crab, *Liocarcinus depurator* (L.) being the favoured food target in one study (Evans *et al*., 1996). *B. undatum* fishermen maintain that higher CPUE is achieved with the use of *Cancer pagarus* (L.) as bait (J. Skillen pers. comm., June 2016).

1.1.2 Growth

A common measure of *B. undatum* size is total shell length (TSL). The highest reported *B. undatum* TSL is currently 122 mm in Shetland (Shelmerdine *et al*., 2007). The shell is made up of 7 – 8 whorls, with the body whorl accounting for 70% of TSL (Ager, 2008). The life history traits of *B. undatum* can be described as classically ‘K-selected’, with a high longevity and slow growth rate. The annual shell growth rate decreases with increasing age (Kideys *et al*., 1993). Significant differences in TSL and Von Bertalannfy growth parameters have been observed in *B. undatum* populations separated by relatively short distances, such as the east and west of Shetland (Shelmerdine *et al*., 2007). *B. undatum* typically has a lifespan of 10 years (Santarelli & Gros, 1985), but through operculum striae aging analysis, has been reported to reach ages up to 12 years (Shelmerdine *et al*., 2006). The age of onset of sexual maturity is also variable, ranging from 3.9 to 6.9 years in South England and West Shetland respectively. This variation in population characteristics at a regional scale poses challenges for the management of commercially exploited *B. undatum*. A high-quality local evidence base for the parameters of *B. undatum* populations is essential for the effective management of this species (Shelmerdine, 2007; Haig *et al*., 2015).

1.1.3 Reproduction

The current body of work points towards an annual breeding cycle for *B. undatum*, a common feature of high-latitude invertebrates (Himmelman & Hamel, 1993; Kideys *et al*., 1993; Valentinsson, 2002). European populations of *B. undatum* generally breed in autumn and winter (de Vooys & van der Meer, 2010). Kideys (1993) concluded that the main egg-laying period occurred from late December to January near Douglas, Isle of Man. Female *B. undatum* attract males using
pheromones, once water temperatures rise to approximately 9 – 12 °C (Hancock, 1967). Females can store sperm from multiple males and control the timing of internal fertilisation to coincide with optimal environmental conditions (Fretter & Graham, 1994). Eggs are laid on hard substrate and contained within capsules (approximately 2700 eggs per capsule) (Fig. 2) (Martel et al., 1986). Larval development occurs within the capsules for 3 – 8 months, after which the juvenile *B. undatum* emerge and crawl onto the benthic substrate (Martel et al., 1986). This reproductive strategy, with highly limited larval dispersal and no broadcast spawning, leads to the formation of geographically isolated sub-populations of *B. undatum*. This isolation can occur over relatively small spatial scales, with reports of genetically distinct populations of *B. undatum* occurring over separation distances of 1 – 2km (Weetman et al. 2006).

**Fig. 2.** Female *Buccinum undatum* (L.) laying a mass of egg capsules, England. Image source: Lawler, 2013

### 1.2 *Buccinum undatum* (L.) fisheries

#### 1.2.1 Fishing methodology

*B. undatum* is fished using baited pots. Rope is used to link a number of pots together in series, forming a line of approximately 20 – 50 pots, with an 18 – 20m spacing between each pot (Lawler and Vause, 2009; Robson, 2014; Robinson, 2015). The soak time (time that baited pots remain on the sea floor) for each string of pots is usually 24 – 48 hours, as bait becomes ineffective after 72 hours of soaking (Lawler and Vause, 2009; Robson, 2014; Robinson, 2015). Pots are baited with waste fish and shellfish, commonly edible brown crab (*Cancer pagarus* L.) mixed with catshark *Scyliorhinus* spp. (Fahy, 2001). In order to comply with minimum landing size (MLS) legislation (70mm TSL in the Isle of Man (IOM)), each catch is passed through a riddle, which is an array of parallel metal bars. There is a specific spacing between the bars, which causes undersized *B. undatum* to fall through and collect in a container before being returned to the sea, whilst the remaining individuals that are above the MLS are collected in sacks prior to landing.
1.2.2 Relevance of *Buccinum undatum* (L.) fisheries

*B. undatum* is commercially exploited in a number of European countries in the northern Atlantic, including Belgium, France, Iceland, Ireland and the UK (Nasution and Roberts, 2004; Shelmerdine *et al.*, 2007). Declines in *B. undatum* abundance have been reported in a number of North Atlantic fisheries as a result of fishing pressure (Cadée *et al.*, 1995; Morel & Bossy, 2004; de Vooys & van der Meer, 2010). Severe reductions of *B. undatum* abundance occurred in the Dutch Wadden Sea in the mid-20th century, leading to local extinction of *B. undatum* in 1991 (Cadée *et al.*, 1995). This was though to be due to a combination of overfishing and imposex caused by tributylin-based antifouling paints (Cadée *et al.*, 1995; Mesink *et al.*, 1996). The case of the Wadden Sea extinction event demonstrates the potential vulnerability of *B. undatum* stocks to overfishing and the importance of effective evidence-based management of these stocks.

In the UK, the *B. undatum* fishery has been expanding since the 1990’s, primarily due to increasing demand in the Far East, particularly South Korea and Japan (Fahy *et al.*, 2003; Morel & Bossy, 2004). The expansion of the *B. undatum* fishery is still in process, with landings in the UK, by UK vessels, increasing from 11.3 thousand tonnes in 2005, to 19.7 thousand tonnes in 2014 (Fig. 3; MMO, 2016). This equates to an increase in value at first sale from £6.8 million to £16.2 million over the same period (MMO, 2016).

![Fig. 3.](image)

Fig. 3. The annual landings (by weight) of *Buccinum undatum* (L.) (10^3 tonnes) in UK waters by UK vessels, from 2005 to 2014. Data sourced from MMO, 2016
1.2.3 Buccinum undatum (L.) fisheries in the Isle of Man

589 tonnes of *B. undatum* were landed in the Isle of Man in 2014, making the *B. undatum* fishery the third largest on the island in terms of landings, behind king and queen scallop fisheries (DEFA, 2016). This level of landings equates to an annual value of £508,000 (DEFA, 2016). The fishery has seen a rapid expansion in recent years; landings of *B. undatum* from IOM territorial waters in 2011 were 132.64 tonnes (Hanley *et al.*, 2013). This trend is likely to continue as fishing effort continues to be increasingly redirected towards non-quota species such as *B. undatum* (Hanley *et al.*, 2013). There is a need for increased research into the status of *B. undatum* stocks around the IOM to assist with any management decisions that are made in response to this increase in fishing effort (Kaiser *et al.*, 2008).

The Isle of Man is a Crown Dependency, and as such has full autonomy over the management of its territorial waters. *B. undatum* fishing, along with all other commercial fishing activity, is managed by the Department of Environment Food and Agriculture. *B. undatum* fishing is subject to ‘The Sea-Fisheries (Whelk Licensing, etc.) Bye-Laws 2007’. A non-transferable licence to fish whelks must be obtained, which has a maximum pot limit per licence of 600 pots. There is a total pot limit of 3600 inside 3 nautical miles, intended to limit overall effort in the fishery (Tynwald, 2016). The minimum landing size (MLS) for *B. undatum* in Manx waters is a total shell length (TSL) of 70mm, compared with 45 mm in the UK, and similarly 45mm under EU regulation. The MLS is designed to be set above the size at sexual maturity (SAM) of an exploited species, thereby ensuring that a proportion of the spawning stock will remain uncaptured and will be able to breed successfully. This increases the likelihood of continued recruitment to the fishery in future years. The MLS of 70mm in the IOM is a precautionary measure, as specific SAM values for the *B. undatum* surrounding the IOM are not currently known.

The Isle of Man government has created a ‘Future Fisheries’ five-year strategy for the sustainable development of the IOM’s sea fisheries and marine environment (Tynwald, 2016). Particularly relevant to the IOM *B. undatum* fisheries are the priority action areas outlined in the Future Fisheries document, aiming to:

- achieve an appropriate level of fishing effort
- achieve sustainable stocks
- produce science data for all stocks
- implement regionally-relevant management

In order to achieve these objectives for the *B. undatum* fishery in the IOM, it is necessary to estimate the number of *B. undatum* present in IOM territorial waters and to elucidate how their density and population characteristics – such as size at maturity – vary regionally.
1.2.4 **Mark-recapture studies of Buccinum undatum** (L.)

When directly counting the number of individuals in a population is not feasible, as is often the case in fisheries science, mark-recapture techniques can be useful for estimating the size of populations. The most commonly used technique is the Lincoln-Peterson index methodology as follows: firstly, a sample of the population is captured and marked. The mark should be designed in a way that will be easily recognisable when encountered again. The marked individuals are then released back into the population. Sufficient time is allowed to pass in order to ensure that the tagged sample of individuals has evenly mixed throughout the population. Then, a second sample is captured. Provided even mixing of marked and unmarked animals has occurred, the ratio of marked to unmarked individuals in the second sample should be equal to the ratio of initially marked individuals to the total population (Lettink & Armstrong, 2003).

The accuracy of this method is reliant upon a number of assumptions being met (Lockwood & Schneider, 2000):

1. There are no births, deaths or emigrations during the study (in other words – a closed population)
2. All individuals have the same probability of being caught
3. Marks are not lost during the study period
4. Sufficient time passes after the initial marking for individuals to become randomly dispersed throughout the population

Recent Lincoln-Peterson studies of *B. undatum* populations have used rubber bands to mark individuals. A thick rubber band is stretched over the shell of the individual, leaving the band around the body whorl of the *B. undatum* shell and ensuring the band does not cover the shell aperture or inhibit movement (Lawler, 2009; Robson, 2014; Robinson, 2015). A 100% retention rate of rubber bands over a period of 4 months has been reported in *B. undatum* tagged in aquaria, suggesting rubber bands are an effective tagging method, fulfilling the assumption of no mark-loss in closed population mark-recapture studies (Robson, 2014).

Robson (2014) also tested the effect of disturbance on the righting (after turning individuals over) and recovery time of *B. undatum* in experimental aquaria. It was found that exposure to air and simulated riddling had no significant effect on the righting time or feeding response times of *B. undatum* (Robson, 2014). This is an important finding as it suggests that the tagging process should not have long term effects on the *B. undatum*, so assumption number 2 (see above) of the Lincoln-Peterson index is likely to apply to both tagged (physically disturbed) and untagged individuals.
1.3 Aim
This project aims to assess the abundance and population characteristics of *Buccinum undatum* (L.) in an area under consideration for development as an offshore windfarm, approximately 8.5 nautical miles east of Douglas, Isle of Man. No data currently exists for the *B. undatum* population within this area, so this study will act as a baseline survey, providing an evidence base to inform future management and assessments of the potential effects of the proposed windfarm development. This study consists of a Lincoln-Peterson mark recapture study, in collaboration with a commercial pot fisher, to estimate the abundance, movement and economic value of the *B. undatum* population. An analysis of catch per unit effort over the duration of the study is also conducted. Laboratory dissection analysis in this study aims to describe the size at maturity, length-weight relationship and total shell length distribution of the *B. undatum* population in the proposed windfarm area.

1.4 Hypotheses
In addition to the baseline data produced by this study, the following hypotheses will be tested:

H₁ = Population abundance of *B. undatum* in the windfarm area will be different to Ramsey Bay, Isle of Man (Robinson, 2015)

H₂ = Mean movement speed of *B. undatum* in the windfarm area will be different to Ramsey Bay, Isle of Man (Robinson, 2015)

H₃ = The total shell length distribution of *B. undatum* in the windfarm area will be different to Ramsey Bay, Isle of Man (Robinson, 2015)

H₄ = Catch per unit effort will be different between ‘stand-up’ and ‘lay-down’ pot types
2. Methodology

2.1 Survey area

The study was carried out within an area currently Agreed for Lease (AfL) to DONG Energy Power (UK) Ltd. for the development of an offshore windfarm (Fig. 4), approximately 8.5 nautical miles east of Douglas, Isle of Man. Benthic habitat surveys, carried out in 2008, suggest that the windfarm area is made up of circalittoral coarse sediment/circalittoral mixed sediment (White, 2011), based on the Marine Habitat Classification for Britain and Ireland Version 04.05 (Connor et al., 2004). There is an existing B. undatum fishery within the leased windfarm area, which is exploited throughout the year (J. Emmerson pers. comm., June 2016). The mark-recapture experiments were carried out in 3 x 1km² sample boxes, located at randomly generated coordinates within the leased windfarm area (Fig. 4). For the duration of the mark-recapture surveys, each 1km² sample box was closed to fishing, other than sampling carried out by the collaborating fishing vessel, in order to have confidence that the data produced had not been affected by unaccounted fishing activity.

Fig 4. Map of the Isle of Man, Britain, showing the offshore windfarm Agreement for Lease site, within which 3 x 1km² sample boxes were fished for Buccinum undatum (L.) during the mark-recapture study, from 14th June – 24th July 2016. Precise locations of the sample boxes are not shown to protect the commercial interests of the fishers involved.
2.2 Fishing vessels

The initial tagging of *B. undatum* for the mark recapture survey was carried out on board the Department of Environment, Food and Agriculture (DEFA) owned fisheries protection vessel (FPV) ‘Barrule’ on the 14th, 15th and 23rd of June 2016. All other sampling was carried out aboard the fishing vessel (FV) ‘Boy Shane’ during the period 23rd June – 24th July. FV *Boy Shane* is a 7.95m catamaran, equipped with a winch and roller for lobster, crab and whelk pot fishing (Fig. 5).

![Commercial fishing vessel 'Boy Shayne'](image)

**Fig. 5.** The commercial fishing vessel ‘Boy Shayne’ used for the recapture phase of the mark-recapture survey of *Buccinum undatum* (L.) in the offshore windfarm Area for Lease, east of the Isle of Man, from 23rd June to 24th July 2016.

2.3 Fishing gear

Four different strings of pots were used for *B. undatum* sampling during the study period (Table 1). Pots were spaced equally along each string with an approximate distance of 20m between each pot. Two different pot types were used – ‘stand-up’ and ‘lay-down’ pots, (Fig. 6). Stand-up pots consisted of plastic-moulded, barrel-shaped pots with 33cm diameter, 35cm height and 36l capacity. Stand-up pots were weighted with a lead base and had 2cm diameter drainage holes. Lay-down pots, plastic-moulded and box shaped, had dimensions of 35cm x 25cm x 18cm, with 2cm diameter drainage holes and bases weighted with steel bars. Each pot design utilised a netted opening which is drawn closed whilst fishing, allowing entry but preventing escape of *B. undatum*. Pots were baited with a mixture of edible crab (*Cancer pagarus* L.) and catshark (*Scyliorhinus canicula* L. or *Scyliorhinus stellaris* L.). *C. pagarus* bait was in the form of de-clawed crabs (waste product from processing). After hauling, the remaining bait in each pot was discarded and replaced. Soak time (the time that pots remain on the sea floor) for baited pots in this study was 24 – 48 hours.
### Table 1

<table>
<thead>
<tr>
<th>String number</th>
<th>Pot type</th>
<th>Number of pots</th>
<th>Pot capacity (l)</th>
<th>Length (cm)</th>
<th>Width (cm)</th>
<th>Height (cm)</th>
<th>Drainage hole diameter (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Stand-up</td>
<td>27</td>
<td>36</td>
<td>33</td>
<td>33</td>
<td>35</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>Stand-up</td>
<td>19</td>
<td>36</td>
<td>33</td>
<td>33</td>
<td>35</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>Lay-down</td>
<td>22</td>
<td>20</td>
<td>35</td>
<td>25</td>
<td>18</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>Lay-down</td>
<td>26</td>
<td>20</td>
<td>35</td>
<td>25</td>
<td>18</td>
<td>2</td>
</tr>
</tbody>
</table>

---

**Fig. 6.** Photographs of typical A) Stand up pots and B) Lay down pot used for the capture of *Buccinum undatum* (L.). Image source: FAFB, 2016

---

### 2.4 Mark-recapture survey

#### 2.4.1 Tag design

A tag design utilising lobster claw bands with unique identification codes, as described in Robinson (2015), was used. The unique identification codes were printed onto 9mm width hard plastic embossing tape using a ‘Dymo Omega’ handheld embossing label machine. A hole was then punched in the embossing tape, allowing it to be attached to the rubber lobster claw band (20mm x 10mm x 1mm) using a plastic snap-lock fastener (Fig. 7). The unique identification codes were made up of a letter (A, B or C) denoting the 1km² sample box that the batch was released in, followed by a unique numeric value. The identification codes allowed for the movement tracking of recaptured individuals.
2.4.2 Tagging and release phase

*B. undatum* were fished from boxes A, B and C using a string of 20 pots on the 14th, 15th and 23rd of June, 2016, by the Fishing Vessel (FV) Boy Shane (Table 2, Fig. 5). Every captured *B. undatum* (without riddling) was then transferred at sea to the Fisheries Protection Vessel (FPV) Barrule in ‘onion sacks’. The sacks of captured *B. undatum* were placed into clean plastic storage drums containing seawater. Fresh seawater was continually pumped into the drums using the FPV Barrule’s pump system, ensuring parameters such as O$_2$ concentration and temperature remained within acceptable thresholds, minimising stress to the captured individuals. Drums were located away from direct sunlight. The captured *B. undatum* were then tagged using stainless steel lobster banding tools, applying the lobster claw bands around the body whorl of the shell, whilst ensuring the shell aperture remained uncovered. The embossed label was positioned so as not to inhibit locomotion of the *B. undatum* (Fig. 7B).

The tagged *B. undatum* were released at random locations within the sample boxes in batches of 100. All individuals within a batch were coded with embossed labels from a consecutive series of 100 (e.g. C101 – C200). In order to minimise physical stress, release batches were lowered to the sea surface in a basket before being tipped out. For each batch of released *B. undatum*, time, date, GPS location, tag code series and number of individuals released was recorded.
Whilst tagging occurred aboard the FPV Barrule, total shell length (TSL) measurements of as many *B. undatum* as time allowed were taken using Vernier callipers. 296, 157 and 249 TSL measurements were taken for study areas A, B and C respectively.

### 2.4.3 Recapture phase

The recapture period in each study area began with an initial fishing effort, in collaboration with the FV Boy Shane, of 4 strings, totalling 94 pots (strings described in Table 1). This recapture effort occurred on 23rd June, 25th June and 07th July in study areas A, B and C respectively. This meant that the time between release and recapture was 9, 10 and 14 days in study areas A, B and C respectively. For each string hauled within the study area, the start and end point of the string was recorded using the on-board GPS system. When a marked *B. undatum* was recaptured, the identification code and pot number was recorded. The pot number allowed for precise positioning of the location of recapture (assuming equal spacing of pots along the length of the string). Due to time constraints, pot number could not be recorded for study area C, so recapture location was considered to be the midpoint of the string. The time, date and total number of sacks of unmarked *B. undatum* were recorded for each string. The total number of *B. undatum* in 10 full sacks was counted and averaged to provide a mean value for the number of individuals per sack. This value was used to estimate the number of unmarked *B. undatum* caught per string. Following the initial recapture sessions, further strings were fished in study area C on 12th, 14th and 24th of July. Due to the low movement speed of *B. undatum* (15 m day\(^{-1}\) (Robinson, 2015)), these later recaptures were considered to be part of the same capture session and the assumption of a closed population within the 1km\(^2\) study areas was considered to be satisfied for these recaptures.

#### Table 2. The total number of marked *Buccinum undatum* (L.) released in each 1km\(^2\) study area during the release phase of the Lincoln-Petersen mark-recapture study in the Area for Lease offshore windfarm area, east of the Isle of Man, from 14th–23rd June 2016.

<table>
<thead>
<tr>
<th>Study area</th>
<th>Number of <em>B. undatum</em> released</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1218</td>
<td>14/06/16</td>
</tr>
<tr>
<td>B</td>
<td>794</td>
<td>15/06/16</td>
</tr>
<tr>
<td>C</td>
<td>710</td>
<td>23/06/16</td>
</tr>
</tbody>
</table>
2.5 Laboratory dissection analysis

In addition to the mark-recapture analysis carried out in this study, 84 non-riddled *B. undatum* sampled from the AfL windfarm area on 14/07/16 were analysed in the laboratory for size, weight and maturity. The sampled individuals were kept frozen and defrosted prior to dissection. Each individual was weighed wet after removing epifauna from the shell to obtain total weight (in grammes to two decimal places). Total shell length was recorded to the nearest 0.1mm using Vernier callipers (Fig. 8). *B. undatum* were then removed from their shells. The digestive whorl, distal from the foot and connective tissues, was dissected away and weighed in order to give gonad weight (g). Individuals were sexed according to the presence or absence of a penis. The penis length of males was measured to the nearest mm from the distal join to the tip of the penis.

Maturity was determined visually, by observing the colour differentiation of the gonad, presence of a vas deferens in males and length of penis in males. One of three maturity stages was assigned according to these observations (Table 3).

![Fig. 8](image.png) **Fig. 8.** Photograph showing the orientation of the *Buccinum undatum* (L.) shell when using Vernier callipers to measure total shell length (mm)
Table 3. Methodology for the visual assessment of male and female *Buccinum undatum* (L.) maturity stage.

<table>
<thead>
<tr>
<th>Maturity stage</th>
<th>Females</th>
<th>Males</th>
</tr>
</thead>
<tbody>
<tr>
<td>Immature</td>
<td>Gonad non-differentiated from digestive whorl</td>
<td>Gonad non-differentiated from digestive whorl. Vas deferens invisible.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Penis length likely &lt; 25mm</td>
</tr>
<tr>
<td>Developing</td>
<td>Gonad beginning to differentiate on anterior edge of digestive whorl</td>
<td>Gonad beginning to differentiate on anterior edge of digestive whorl. Vas deferens may be visible.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Penis length likely &lt; 25mm</td>
</tr>
<tr>
<td>Mature</td>
<td>Ovary fully differentiated from digestive whorl</td>
<td>Testis fully differentiated from digestive whorl. Vas deferens clearly visible.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Penis length likely &gt; 25mm</td>
</tr>
</tbody>
</table>

3. Data analysis

3.1 Mark-recapture analyses

3.1.1 Catch per unit effort (CPUE)

The mean CPUE for *B. undatum* was calculated for individual strings fished during the mark-recapture study. The total number of full sacks landed per string was multiplied by a mean weight of a full sack in the June – July 2016 period (38kg (J. Skillen pers. comm., July 2016)). The weight of *B. undatum* per string was then divided by the number of pots on the string to give a mean CPUE in kg pot\(^{-1}\). As the mean weight of a full sack of *B. undatum* was based on the weight of landed sacks (after riddling), the CPUE values calculated accounted for *B. undatum* over the MLS of 70mm only. Mean daily CPUE values were produced for all days that were fished during the study period 23\(^{rd}\) June – 24\(^{th}\) July 2016. All strings fished during a single day were averaged to produce a single mean daily CPUE. Mean daily CPUE (±95% CI) was displayed graphically.

3.1.2 Pot type

CPUE effort data (see section 3.1.1) was used to produce overall mean CPUE for both stand-up and lay-down pot types. Differences in mean CPUE values between pot types was tested for significance using a one-way analysis of variance (ANOVA). Before conducting ANOVA testing, the data was tested for normality using a Shapiro-Wilk test and for homogeneity of variance using a Levene’s test. As the data met these criteria, the parametric ANOVA test was used. Mean CPUE (±95% CI) was displayed graphically for both stand-up and lay-down pots.
3.1.3 Movement

The GPS co-ordinates of the release and recapture points of each marked *B. undatum* were recorded during the mark recapture study. As each marked individual had a unique identification number, it was possible to track the minimum movement distances of each recaptured individual. Where possible, the number of the pot containing recaptured individuals was recorded, allowing more precise positioning of recapture points to be calculated in QGIS v 2.8 (assuming equal spacing of pots along the length of a string). If pot number could not be recorded due to time constraints, the GPS position of recapture was considered to be the midpoint of the string. Precise recapture positions (based on pot number of recapture) were possible for study areas A and B, whilst the midpoint of the string was used in area C. The minimum movement distance assumes that individuals travel in a straight line between release and recapture points. Release and recapture points were plotted in QGIS v 2.8 using the British National Grid projected coordinate system. The distance between these points was measured in QGIS and then divided by the time taken between release and recapture to give movement speeds (m day\(^{-1}\)).

3.1.4 Lincoln-Petersen index

Estimates of *B. undatum* population size within each 1km\(^2\) study were generated using the Lincoln-Petersen index. The original form of this estimator is structured in the following way:

\[
N = \frac{Kn}{k}
\]

Where:

- \(N\) = Total estimated population
- \(K\) = Total number of individuals caught during the second sampling occasion
- \(n\) = Total number of individuals caught in the first sampling occasion
- \(k\) = Number of marked individuals caught in the second sampling occasion

The usage of this estimator in this study required the following assumptions to be made (Lockwood & Schneider, 2000):

1. There are no births, deaths or emigrations during the study (in other words – a closed population)
2. All individuals have the same probability of being caught
3. Marks are not lost during the study period
4. Sufficient time passes after the initial marking for individuals to become randomly dispersed throughout the population
The original form of the Lincoln-Petersen estimator is known to have a tendency to overestimate population size so a modified unbiased estimator has been used in this study, as described by Seber (1982). This follows the formula:

\[ N = \frac{(K + 1)(n + 1)}{(k + 1)} - 1 \]

95% confidence intervals were produced for the *B. undatum* abundance estimates for each 1km\(^2\) study area using 95% Poisson confidence intervals for the value of \(k\) (recaptured marked individuals) as described in Krebs (2014).

A mean value for the number of *B. undatum* km\(^2\) was produced by averaging the Lincoln-Petersen estimates for study areas B and C. Study area A was omitted from further analysis as only a single recapture was achieved, giving an inflated abundance estimate. When compared to areas B and C, it was decided that the single recapture was anomalous, and therefore was unlikely to provide accurate abundance estimates for study area A.

3.1.5 Population density

Whilst each study box (A, B and C) was designed to be 1km\(^2\), there was slight variation in the placement of the vertex GPS coordinates. Values for the areas of each study box were calculated with greater precision using QGIS v 2.8 (British National Grid projected coordinate system). Coordinates for the study box vertices were plotted and converted to polygons. Areas of the polygons were then calculated in m\(^2\). Lincoln-Petersen abundance estimates for each study box were divided by the calculated areas to produce population density estimates (individuals m\(^{-2}\)). A mean value of population density was produced from study areas B and C.

3.1.6 Valuation of the windfarm area for lease

QGIS v 2.8 (British National Grid projected coordinate system) was used to calculate the total area (m\(^2\)) of the windfarm area for lease. The total area was multiplied by the previously calculated mean density (individuals m\(^{-2}\)) of *B. undatum* to produce a total abundance estimate for the entire windfarm area. This abundance value was divided by the average number of *B. undatum* per sack from a subsample of 10 (402.6; Table 4) and multiplied by the value at first sale of each sack, £32 (J. Skillen pers. comm., July 2016), giving an estimate for total potential value of the *B. undatum* fishery to the local fishermen. 1.27% of measured *B. undatum* from the windfarm AfL had a TSL under the MLS of 70mm, so the valuation estimate was reduced by this amount. 95% confidence intervals for the value estimation were produced using the upper and lower limits produced for the Lincoln-Petersen abundance estimates (as described in section 3.1.4).
3.2 Laboratory dissection data analysis

All statistical analyses were run in R version 3.2.1 (R Core Team 2015).

3.2.1 Sexual maturity

Prior to any maturity analyses, maturity-stage data (see Table 3) was transformed into binary form (1 = mature, 0 = immature). Of the 84 samples analysed, the number categorised as ‘Beginning to mature’ was nil. Data was subset into male and female. Estimated morphological length-at-maturity in males was calculated by determining the breakpoint in the linear relationship between penis length (mm) and TSL (mm). This breakpoint was considered to be the point at which sexual maturation occurs. This was achieved using an iterative search procedure, using the following model (Crawley, 2012):

\[
y \sim x \cdot I(x < c) + x \cdot I(x > c)
\]

Where:

- \( y \) = penis length
- \( x \) = total shell length
- \( * \) = main effects and interactions for both variables
- \( c \) = breakpoint

\( I(x<c) \) and \( I(x>c) \) = binary dummy variables that equate to 1 or 0 depending on the truth/falsity of the statement within the parenthesis

The value of \( c \) that produced the lowest residual mean standard error in the iterative search procedure was considered to be the true value of \( c \).

Estimated functional length-at-maturity was determined for each sex using a logistic regression model (Roa et al. 1999), reformulated by Walker (2005) to produce the model:

\[
P_{TSL} = \left( P_{MAX} \cdot \left( 1 + e^{-\ln(19) \left( \frac{1-\beta_1}{\beta_2-\beta_1} \right)} \right)^{-1} \right)
\]

Where:

- \( P_{TSL} \) = the proportion of the population mature at a given TSL
- \( \beta_1 \) and \( \beta_2 \) = curve parameters corresponding to \( l_{50} \) and \( l_{95} \) respectively
- \( P_{MAX} \) = the asymptote
Parameters $\beta_1$ and $\beta_2$ were estimated using a generalised linear model (GLM) with a logit-link function and a binomial error structure. 95% confidence intervals were produced by bootstrapping the data (10,000 runs). The significance of fitted models was determined by comparing the deviance explained by the models relative to the null model with chi-squared tests. The original code for this analysis was written by Harry, A. V. (Harry, 2013) and was modified for the current study by Emmerson, J., Bangor University.

3.2.2 Length-weight relationship

The relationship between total weight (g) and TSL (mm) was plotted graphically and determined using the power curve function $W = aL^b$, where $W$ is total weight (g), $L$ is the TSL (mm), and $a$ and $b$ are constants (King, 2007). The value of the constants were determined using a linear regression analysis of the log-transformed data, where $Ln(W) = Ln(a) + bLn(L)$. The significance of sex as a factor and the interaction between sex and TSL was ascertained using an Analysis of Covariance (ANCOVA) procedure, in order to determine whether males and females had different length-weight relationships. Values of $b$ close to 3.0 are considered to denote isometric growth i.e. TSL increases in proportion to increases in weight. Values of $b$ below 3.0 suggest negative allometric growth (an over-proportional increase of length compared to weight), whilst values of $b$ greater than 3.0 suggest positive allometric growth (over-proportional increase of weight compared to length) (Froese, 2006; King, 2007).

3.2.3 Total shell length distribution

TSL data from the laboratory analysis and from measurements taken aboard the FPV Barrule during the mark-recapture phase of this study were combined to produce an overall TSL dataset (n = 786) of non-riddled for the windfarm area for lease (AfL). TSL data (n = 500) from a previous study carried out in Ramsey Bay, Isle of Man, from June – July 2015 was also included in the analysis for comparison (Robinson, 2015).

Violin plots with inset box plots were produced to display TSL distributions from the windfarm AfL (2016) and Ramsey Bay (2015) graphically. Due to the non-normality of the distributions (tested with a Shapiro-Wilk test), a non-parametric Kruskal Wallis test was performed to test for differences in median values of TSL between the Ramsey Bay (2015) and the windfarm AfL (2016).
4. Results

4.1 Mark-recapture analyses

4.1.1 Catch Per Unit Effort (CPUE): June – July 2016

The mean overall CPUE of *B. undatum* for all pots fished during the study (±95% confidence intervals (CI)) was 2.94 (±0.42) kg pot\(^{-1}\). Mean daily CPUE was variable, ranging from 2.20 (±0.95) to 4.28 kg pot\(^{-1}\) (Fig 9). CPUE also varied between different strings fished throughout a given day, with the greatest variation occurring on 25/06/2016, with string CPUE ranging from 0.86 to 2.96 kg pot\(^{-1}\).

![Mean CPUE (kg pot\(^{-1}\))](image)

**Fig. 9.** The mean (±95% CI) daily CPUE of *Buccinum undatum* (L.) in kg pot\(^{-1}\) landed in the windfarm Area for Lease (AfL), east of the Isle of Man, from 23rd June to 24th July 2016. No confidence interval was produced for 24/07/2016, as only a single string within the windfarm AfL was fished.

4.1.2 Pot type

304 stand-up and 164 lay-down pots were fished during the mark-recapture phase of the project 23rd June to 24th July 2016. Mean CPUE (±95% CI) for stand-up pots was 3.00 (±0.45) kg pot\(^{-1}\). CPUE in lay-down pots was more variable, with a lower mean of 2.85 (±0.83) kg pot\(^{-1}\) (Fig. 10).

Differences in mean CPUE between stand-up and lay-down pots were non-significant (One-way ANOVA, F\(_{1,15}\) = 0.111, P = 0.744).

![Mean CPUE (kg pot\(^{-1}\))](image)

**Fig. 10** Comparison of the mean (±95% CI) CPUE of *Buccinum undatum* (L.) in kg pot\(^{-1}\) between stand-up and lay-down pot types. Pots were landed in the windfarm Area for Lease, east of the Isle of Man, from 23rd June to 24th July 2016.
### 4.1.3 Lincoln-Peterson index

A total of 1218, 794 and 710 *B. undatum* were captured, tagged and released in the 1km² study areas A, B and C respectively. Study area A had the least recaptures, with only a single recapture (0.08% of the number released). Study areas B and C had similar recaptures, 22 and 21 respectively (2.77% and 2.96% of the total number released). Taking all study areas together, there was an overall recapture rate of 1.62%. No *B. undatum* were recaptured in study area C with the initial 4 strings of fishing effort. All 21 recaptures in box C occurred from additional strings fished on 12th, 14th and 24th July (Fig. 13).

In order to produce Lincoln-Petersen abundance estimates for each study area, it was necessary to estimate the total numbers of unmarked *B. undatum* caught in the recapture phase of the survey. An average value for the number of *B. undatum* individuals contained within a full whelk sack was calculated from a subsample of 10 sacks. The mean number (± 95% CI) of *B. undatum* in each full whelk sack was 402.6 (±5.15) (Table 4). This mean value was multiplied by the number of sacks of unmarked *B. undatum* landed, to produce the total numbers of unmarked *B. undatum* caught in the recapture phase of the survey.

<table>
<thead>
<tr>
<th>Sack number</th>
<th>Number of individuals</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>403</td>
</tr>
<tr>
<td>2</td>
<td>408</td>
</tr>
<tr>
<td>3</td>
<td>407</td>
</tr>
<tr>
<td>4</td>
<td>396</td>
</tr>
<tr>
<td>5</td>
<td>398</td>
</tr>
<tr>
<td>6</td>
<td>390</td>
</tr>
<tr>
<td>7</td>
<td>392</td>
</tr>
<tr>
<td>8</td>
<td>411</td>
</tr>
<tr>
<td>9</td>
<td>415</td>
</tr>
<tr>
<td>10</td>
<td>406</td>
</tr>
<tr>
<td>Mean</td>
<td>402.6</td>
</tr>
</tbody>
</table>

Table 4. The total number of *Buccinum undatum* (L.) counted in 10 full whelk sacks after landing. The mean value of the number of individuals per full sack was used to calculate the total number of unmarked *B. undatum* caught in the recapture phase of the Lincoln-Petersen surveys in areas A, B and C, located in the windfarm area for lease, east of the Isle of Man.

The Lincoln-Petersen abundance estimate for study area A (1.50 x 10⁶ individuals) is unlikely to be accurate, due to the low recapture rate (1 recapture). This increased likelihood of inaccuracy is reflected by an abundance estimate for study area A that is 7.2 and 6.4 times greater than B and C...
respectively (Table 5). Study area A was therefore removed from further analysis. Study areas B and C produced similar Lincoln-Petersen abundance estimates of 207,287 and 233,724 respectively (Fig. 11).

The areas of sample boxes B and C, calculated using QGIS, were 1,058,065 and 1,071,566 m$^2$ respectively. Based on these calculated areas, the density of *B. undatum* in areas B and C was 0.19 and 0.21 (Fig. 12). Confidence intervals for abundance and density estimates in each study area are displayed in Table 5. The overall mean population density (±95% CI) for the windfarm AfL (excluding study area A) was 0.20 (lower CI = 0.14, upper CI = 0.32) individuals m$^{-2}$.

![Graph showing estimated abundance and density for *Buccinum undatum* in areas B and C](image)

**Fig. 11.** Lincoln-Petersen abundance estimates (±95% CI) for *Buccinum undatum* (L.) in survey areas B and C, located in the windfarm area for lease, east of the Isle of Man. Recapture period: 23rd June – 24th July.

![Graph showing density estimates for *Buccinum undatum* in areas B and C](image)

**Fig. 12.** Density estimates (±95% CI) for *Buccinum undatum* (L.) in survey areas B and C, located in the windfarm area for lease, east of the Isle of Man. Recapture period: 23rd June – 24th July.
4.1.4 Movement

The overall mean daily movement speed across all 3 sample boxes (±95% CI) was 9.13 (±3.75) m day$^{-1}$. Mean daily movement speeds within sample boxes ranged from 5.12 to 10.69 m day$^{-1}$ (Table 6). The greatest distance travelled was 815m over a period of 228 hours in sample box B (Fig. 14). More precise locations of recapture were produced for study areas A and B, as the pot number of recaptures was recorded. Pot number was not recorded for study area C so recapture points were defined as midpoints of the string.

Table 6. The mean (±95% CI) movement speeds of *Buccinum undatum* (L.) in survey areas A, B and C, located in the windfarm area for lease, east of the Isle of Man. Recapture period: 23$^{rd}$ June – 24$^{th}$ July.

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B (±95% CI)</th>
<th>C (±95% CI)</th>
<th>Overall (±95% CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td>1</td>
<td>22</td>
<td>21</td>
<td>44</td>
</tr>
<tr>
<td>Mean speed</td>
<td>5.13$^*$</td>
<td>10.69 (±7.19)</td>
<td>7.68 (±2.34)</td>
<td>9.13 (±3.75)</td>
</tr>
</tbody>
</table>

* No confidence intervals produced as n = 1

4.1.5 Valuation of the windfarm area for lease

Based on the calculated value for *B. undatum* density in the windfarm AFL, east of the Isle of Man, and the total area covered by the lease, there is a potential value (±95% CI) of £3.99 million (lower CI = £2.72 million, upper CI = £6.28 million) of *B. undatum* available to be exploited by local potting fishermen in the windfarm area for lease. This value has been corrected for the 1.27% of measured *B. undatum* that had TSLs below the MLS of 70mm.
Fig. 13. All release and recapture locations for *Buccinum undatum* (L.) during the Lincoln-Petersen surveys in areas A, B and C, located in the windfarm area for lease, east of the Isle of Man. Recapture period: 23rd June – 24th July. More precise locations of recapture were produced for study areas A and B, as the pot number of recaptures was recorded. Pot number was not recorded for study area C so recapture points are defined as midpoints of the string. 3 additional strings were fished in study area C after the initial recapture session on 12th, 14th and 24th July.

R = number of *B. undatum* recaptured. Boxes indicate the limits of the study areas.
Fig. 14. Release and recapture locations of recaptured *Buccinum undatum* (L.) during the Lincoln-Petersen surveys in areas A, B and C, located in the windfarm area for lease, east of the Isle of Man. Recapture period: 23rd June – 24th July. Lines indicate the shortest direct path between corresponding release and recapture points. More precise locations of recapture were produced for study areas A and B, as the pot number of recaptures was recorded. Pot number was not recorded for study area C so recapture points are defined as midpoints of the string.

\[ R = \text{number of } B. \text{ undatum recaptured.} \]
4.2 Laboratory analyses

4.2.1 Total shell length distribution

A total of 786 non-riddled *B. undatum* sampled from the windfarm AfL (2016) were analysed for TSL. 500 *B. undatum* TSL measurements from a previous study in Ramsey Bay (Robinson, 2015) were included in the analysis for comparison. The windfarm AfL had the largest mean TSL (±95% CI) of 97.0 (± 0.3) mm, compared to a mean of 90.3 (± 0.5) mm in Ramsey Bay. The range of TSL measurements in the windfarm AfL and Ramsey Bay was 54.7 - 124.0 mm and 31 – 117 mm respectively (Fig. 15). The location parameters of the TSL distributions in the windfarm AfL and Ramsey Bay were significantly different (Kruskal-Wallis, $X^2_{(1)} = 136.74$, $P < 0.001$). Visual analysis of the violin and box plots suggests that the TSL distribution in the windfarm AfL is shifted towards higher TSL values, with a lower proportion of smaller *B. undatum* at the lower end of the distribution (50 – 70mm). The proportion of measured TSL values that fell below the Isle of Man MLS (70mm) was 5.80% in Ramsey Bay and 1.27% in the windfarm AfL. Both locations showed a uni-modal TSL distribution (Fig. 15). There was no significant difference in TSL distributions between the sexes in the windfarm AfL (Kruskal-Wallis, $X^2_{(1)} = 0.59732$, $P = 0.44$).

![Fig. 15. Box and violin plots of total shell length (mm) distributions for *Buccinum undatum* (L.) sampled from the windfarm area for lease (2016) and Ramsey Bay (Robinson, 2015) east of the Isle of Man. Increased width of violin plots indicates increased density of values. Horizontal line indicates the MLS of *B. undatum* in the Isle of Man (70 mm). n = sample size.](image-url)
4.2.2 Maturity analysis

Maximum likelihood estimates of the TSL at which 50% of *B. undatum* were sexually mature (L$_{50}$) in the windfarm AfL, estimated using generalized linear models with logit link functions and binomial error structures, was 69.8 mm for females and 83.8 mm for males (Fig. 16). A lower 95% confidence limit could not be produced for females, due to the low number of immature individuals within the sample (8.1% of sample was immature). The upper 95% confidence limit for female L$_{50}$ was 84.1 mm (Fig. 16). 95% CI for male L$_{50}$ were 77.5 – 87.2 mm (Fig. 16). Both models were highly significant when tested against the null model (Male: Residual deviation = 0.000, df = 28 p < 0.001; Female: Residual deviation = 9.401, df = 35, p < 0.001).

Using an iterative search procedure, an inflection point was identified for morphometric variance in penis length for *B. undatum* > 83.9 mm TSL (Fig. 17), giving a similar maturity estimate (+ 0.1 mm) to the male L$_{50}$ based on visual gonad assessment (83.8mm, Fig. 16).

![Maturity ogive](image.png)

**Fig. 16.** Maturity ogive of model fit for male and female *Buccinum undatum* (L.) sampled from the windfarm area for lease, east of the Isle of Man, on 14th June 2016. The horizontal red lines indicate the proportion at which 50% of the sampled *B. undatum* were sexually mature. Length at 50% maturity is displayed in the bottom right corner of each figure.
4.2.3 Length-weight relationship

The calculated length-weight relationships of male and female *B. undatum* suggest that males have a greater total weight than females for a given TSL, but only at greater lengths (Fig. 18). The slope values for the log-transformed linearised length-weight data were significantly higher in males than females ($F_{1,53} = 8.67$, $P = 0.005$). There was no significant effect of sex on the ‘y-intercept’ of the fitted regressions ($F_{1,54} = 1.53$, $P = 0.22$), further suggesting that the disparity in total weight between the sexes only emerges at higher TSL values. The length-weight relationship for males was described by the curve $W = 1.87 \times 10^{-5} L^{3.37}$ ($r^2 = 0.95$, $P < 0.001$) and for females by $W = 2.8 \times 10^{-4} L^{2.78}$ ($r^2 = 0.94$, $P < 0.001$) (Fig. 18). The $b$ value for males is 3.37, suggesting positive allometric growth. The $b$ value for females is 2.78, suggesting negative allometric growth.

**Fig. 17.** Inflection point indicating an allometric growth pattern based on variance between iterative tests on linear models of penis length (mm) and total shell length (mm) for male *Buccinum undatum* (L.). The dotted black vertical line is the value with the lowest mean standard error (83.9 mm TSL). The dotted red line is the minimum landing size for *B. undatum* on the Isle of Man. Maturity stage, based on visual examination of the gonad, is indicated by the colour of the point. *B. undatum* were sampled from the windfarm area for lease, east of the Isle of Man, on 14th July 2016.
Fig. 18. Length-weight relationships for female and male *Buccinum undatum* (L.) sampled from the windfarm area for lease, east of the Isle of Man on 14th July 2016. Calculated values for the parameters of the length-weight function are displayed. $W =$ weight (g), $L =$ total length (cm).

**Female**

$W = 2.8 \times 10^{-4} L^{2.78}$

- $N = 32$
- $R^2 = 0.94$
- $P < 0.001$

**Male**

$W = 1.87 \times 10^{-5} L^{3.37}$

- $n = 25$
- $R^2 = 0.95$
- $P < 0.001$
5. Discussion

5.1 Mark-recapture analyses

5.1.1 Catch Per Unit Effort (CPUE)

CPUE values, reported as a weight per standardised unit of effort, are often used as proxies for the population abundance of commercially targeted species (Gulland, 1974, Maunder, 2001). The mean (±95%CI) CPUE in the windfarm AfL was 2.94 ±0.42 kg pot⁻¹. This is higher than a number of reported CPUEs in other areas of the UK. In Jersey, Channel Islands, a mean CPUE of 2.09 kg pot⁻¹ over the period 2003 – 2011 was reported (Shrives et al., 2015) and mean CPUEs of 1.3 and 1.4 kg pot⁻¹ were recorded in Oxwich and Swansea Bay, South Wales, June – July 2014, respectively. The CPUE in Jersey was previously higher, at 3.3kg pot⁻¹ during the period 1996 – 2002 (Morel and Bossy, 2004), which is nearer to the CPUE reported in this study. As the Jersey B. undatum population only began to be exploited in 1996, it could be argued that the higher CPUE values found by Morel and Bossy (2004) and this study, reflect populations that are not heavily exploited. Another study carried out in Ramsey Bay, Isle of Man, June – July 2015, reported a CPUE of 3.57 kg pot⁻¹ (Robinson, 2015), evidence to suggest that either B. undatum is not heavily exploited in the territorial waters of the Isle of Man, or that IOM waters are able to support greater densities of B. undatum.

Daily mean CPUE of B. undatum in the windfarm AfL during the study period June – July 2016 was variable, with no pattern apparent. This lack of discernible trend in daily CPUE has been reported in similar studies carried out on B. undatum in Ramsey Bay, Isle of Man (Robinson, 2015) and Oxwich and Swansea Bay, South Wales (Robson, 2014). Trends in CPUE may be better determined over a longer period of time, over an entire fishing season for example. This longer-term approach has been used to suggest seasonal trends in B. undatum CPUE in Camarthen Bay, South Wales. This study found that mean CPUE (kg pot⁻¹) ranged from 1.8kg in March to 3.2kg in July 2011 (French, 2011). However, differences in CPUE values between months could not be isolated from differences in depth and commercial vessels used for sampling.

Whilst temporal trends in CPUE may become apparent over the course of an annual sampling regime, there could be a number of factors affecting the CPUE of B. undatum other than population abundance. Factors such as changes in species density and fishing gear efficiency have also been shown to affect CPUE (Rose and Kulka, 1999; Maunder et al., 2006). B. undatum use chemoreception in order to locate food sources (Bailey & Laverack, 1996; Nielsen, 1974). Therefore, the intensity of, and area occupied by, the bait plume of each pot will have a direct effect on the number of individuals caught. Factors such as current speed, bait type, substratum type and depth have all been shown to have an affect on the area of attraction of baited pots (Himmelman,
Current speed and direction in particular, has been shown to greatly affect the size and shape of the attraction range of baited pots for *B. undatum*, and this factor could vary throughout a single sampling day (Himmelman, 1988; Sainte-Marie, 1991). For this reason, it could be argued that the collection of site specific environmental data, such as current speed and direction, depth, temperature and an understanding of the effects of these variables on the effective fishing range of baited *B. undatum* pots, is important in order to produce corrected CPUE values that have a closer relationship to population abundance. This would allow standardisation of *B. undatum* CPUE data, allowing comparisons to be made both temporally and spatially (Maunder and Punt, 2004).

There was no significant difference in mean *B. undatum* CPUE between lay-down and stand-up pots in the windfarm AfL. This is despite the fact that stand-up pots have a greater capacity, suggesting that pot capacity is not a limiting factor of CPUE. Personal observation aboard the sampling vessel suggested that pots were not at full capacity when hauled. This result is in line with the findings of Robson (2014), who also found no significant difference in CPUE between pot types.

5.1.2 Mark-recapture to estimate abundance

Mark-recapture experiments were initially used to estimate the movement speeds of *B. undatum* and the effective areas of baited pot odour plumes (Himmelman, 1988; McQuinn *et al.*, 1988; Sainte-Marie, 1991). The feasibility of mark-recapture experiments as a means of estimating *B. undatum* abundance, using rubber band tags, was first assessed off the Sussex coast, UK (Lawler & Vause, 2009). Despite low recapture rates (reported to be due to the study being carried out in September - outside of the main *B. undatum* fishing season) this study demonstrated that rubber band tagging methodology was a potentially feasible means of estimating abundance. Further mark-recapture studies using similar methodologies have been carried out on *B. undatum* populations in June – July 2014, South Wales, UK (Robson, 2014) and in June-July 2015, Ramsey Bay, Isle of Man (Robinson, 2015). Whilst both studies were able to produce abundance estimates, due to the collaborative nature of the study with local potting fisherman, and a lack of a defined sampling area, there were issues with standardisation of fishing effort and location, which may have affected Lincoln-Peterson estimates of *B. undatum* abundance and subsequent calculations of density (see section 5.1.4). This study aimed to reduce the effect of these limitations by defining 3 x 1km² sampling boxes for the purposes of the mark-recapture experiment.
The accuracy of the Lincoln-Peterson method is reliant upon a number of assumptions being met (Lockwood & Schneider, 2000):

1. There are no births, deaths or emigrations during the study (in other words – a closed population)
2. All individuals have the same probability of being caught
3. Marks are not lost during the study period
4. Sufficient time passes after the initial marking for individuals to become randomly dispersed throughout the population

The mean daily movement speed estimated in this study (9.13 (±3.75) m day$^{-1}$), multiplied by the longest time interval between the release of a marked individual and recapture (30.66 days, sample box C) gives a total potential movement distance of 279.93m. It is therefore possible that some emigration or immigration could have occurred at the edges of the sample box C, although it is unlikely to have greatly affected assumption number 1, as the majority of sampling occurred away from the edges of the sample boxes.

Tag retention rate is an important factor in Lincoln-Peterson abundance estimations, as assumption 3 requires a 100% tag-retention rate for the duration of the study. Robson (2014) found that in laboratory conditions, $B.\ undatum$ tagged with rubber lobster claw bands of the same type used in this study, had a 100% retention rate over a period of 4 months. Lawler and Vause (2009) reported that degradation of the rubber tags began to occur after 12 weeks in the field. In addition, individuals tagged by Robinson (June, 2015) in Ramsey Bay, Isle of Man, have been recaptured in April of 2016 (J. Emmerson pers. comm., April 2016). Taken together, the evidence suggests that 100% tag retention is likely to have occurred in this study, given that the longest period between tagging and recapture was 30.66 days.

The rubber band tags, with the red embossed label attached, were easily visible aboard the sampling vessel, so all recaptured marked individuals are likely to have been recorded.
5.1.3 Recapture rate

Overall recapture rates in study boxes B and C were consistent, at 2.77% and 2.96 % respectively. This is lower than two recent *B. undatum* mark-recapture studies, but in line with a mark recapture study carried out in North Wales, 2014 (Table 7). Low recaptures of 1 and 0 were achieved in study areas A and C respectively with the initial 4 recapture strings. Recapture rates improved in study area C with additional strings fished at later dates. Recapture rates were also variable in study area B, with many recaptures occurring on a string that was fished close to an area of concentrated release points. This suggests that at the time of initial recapture effort, the released *B. undatum* may have been non-randomly mixed with the rest of the population in areas A and C. Higher recapture rates than those achieved in this study would be desirable in order to reduce the size of the 95% confidence intervals for the Lincoln-Peterson abundance estimates produced. Suggestions for future methodologies are discussed in section 5.3.

<table>
<thead>
<tr>
<th>Source</th>
<th>Location</th>
<th>Mean recapture rate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Robinson(2015)</td>
<td>Ramsey Bay, Isle of Man</td>
<td>15.44</td>
</tr>
<tr>
<td>Robson(2014)</td>
<td>Oxwich Bay &amp; Swansea Bay, South Wales</td>
<td>13.7</td>
</tr>
<tr>
<td>Turtle(2014)</td>
<td>Llyn peninsula, North Wales</td>
<td>3.27</td>
</tr>
<tr>
<td>Current study</td>
<td>Windfarm AfL, East Isle of Man</td>
<td>2.87</td>
</tr>
</tbody>
</table>

Table 7. Results from published literature for mean recapture rates of tagged *Buccinum undatum* (L.) in Lincoln-Peterson mark-recapture studies. Recapture rate is expressed as a percentage of the total marked individuals that are recaptured.

5.1.4 Abundance

Early studies of *B. undatum* density (pre-2000) relied on diving observations and pot fishing (using calculations of density based on the estimated effective area of baited pots). More recent studies (post-2000) have utilised Lincoln-Peterson mark-recapture methodologies to estimate abundance. The movement towards Lincoln-Peterson methodology has also seen a general increase in estimates of *B. undatum* densities. The mean density estimate produced by the current study (0.20 m$^{-2}$) does not follow this trend and is more similar to earlier estimates produced by non-mark-recapture, fishery-independent methodologies (Table 8). In particular, the density estimates produced by Kideys (1993) (also carried out in IOM waters) are highly similar (Table 8). All three studies utilising Lincoln-Peterson methodologies (Table 8) were carried out in collaboration with local fishing vessels and subsequently reported issues with standardisation of fishing effort and location. In effect, the collaborating fishermen, understandably, targeted areas of high *B. undatum* density, whilst quickly moving on from areas that provided lower than expected CPUE. This sustained targeting of seabed that provided high CPUE may have inflated the abundance estimates produced.
in these studies. The current study was also carried out in collaboration with a local fishing vessel, but as the fishing effort and location was contained within the bounds of the predefined 1km² sample boxes, it may be that the issues causing the inflated abundance estimates have been addressed, hence the lower reported density in this study.

Table 8. Results from published literature for densities (individuals per m²) of *Buccinum undatum* (L.) with a range of locations and methodologies.

<table>
<thead>
<tr>
<th>Author</th>
<th>Location</th>
<th>Method used</th>
<th>Density (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hancock (1963)</td>
<td>Thames estuary</td>
<td>Fishing with pots</td>
<td>0.5</td>
</tr>
<tr>
<td>Gros and Santarelli (1986)</td>
<td>Channel Islands</td>
<td>Fishing with pots</td>
<td>0.37</td>
</tr>
<tr>
<td>McQuinn, Gendron and Himmelman (1988)</td>
<td>St. Lawrence estuary</td>
<td>Fishing with pots</td>
<td>0.81</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Diving</td>
<td>0.65</td>
</tr>
<tr>
<td>Kideys (1993)</td>
<td>Douglas Bay</td>
<td>Fishing with pots</td>
<td>0.08 – 0.38</td>
</tr>
<tr>
<td>Legault and Himmelman (1993)</td>
<td>St. Lawrence estuary</td>
<td>Diving (1771 m³ observed)</td>
<td>0.417 ± 0.045</td>
</tr>
<tr>
<td>(Robson, 2014)</td>
<td>Oxwich Bay</td>
<td>Lincoln-Peterson</td>
<td>134</td>
</tr>
<tr>
<td></td>
<td>Swansea Bay</td>
<td>(Pot fishing)</td>
<td>249</td>
</tr>
<tr>
<td>(Turtle, 2014)</td>
<td>Llyn Peninsula</td>
<td>Lincoln-Peterson</td>
<td>3.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Pot fishing)</td>
<td></td>
</tr>
<tr>
<td>(Robinson, 2015)</td>
<td>Ramsey Bay</td>
<td>Lincoln-Peterson</td>
<td>2.68</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Pot fishing)</td>
<td></td>
</tr>
<tr>
<td>(Bolger, 2016)</td>
<td>Windfarm AfL, East Isle of Man</td>
<td>Lincoln-Peterson</td>
<td>0.20</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Pot fishing)</td>
<td></td>
</tr>
</tbody>
</table>
5.1.5 Movement

*B. undatum* in the windfarm AfL had a mean movement speed of 9.13 (±3.75) m day\(^{-1}\). This is similar to mean movement speeds found in other mark-recapture studies, 11 (±1) m day\(^{-1}\) in Oxwich Bay and 10 (±3) m day\(^{-1}\) in Swansea Bay, South Wales (Robson, 2014). In Ramsey Bay, Isle of Man, it was found that recaptured individuals had moved an average of 15.2 (± 7.0) m per day (Robinson, 2015). These mean movement speeds, all produced by recording GPS locations of release and recapture, may be conservative estimates, as they assume a straight line of travel between release and recapture points. Counting the pot number of recaptured *B. undatum* allowed for the production of more precise and informative movement data, as demonstrated by a string with a number of recaptures from different release points in study area B. As *B. undatum* is a chemosensory predator/scavenger, it is likely to display positive chemotaxis towards food odours (Bailey & Laverack, 1996; Mackie et al., 1968; Nielsen, 1974). The incident direction of food odours will change with the tide, so it is reasonable to assume that *B. undatum* movement will be multi-directional, according to the movement of the tides and localised currents. For this reason, total distance travelled (and resulting average movement speeds) could be higher than the results of these mark recapture studies suggest. A study carried out using SCUBA diving, directly observing *B. undatum* movement speeds towards a baited trap, reported maximum movement speeds of 8.3 cm min\(^{-1}\) to 11.4 cm min\(^{-1}\), with maximum daily travel distances of 50m (Himmelman, 1988). This shows that movement speeds of *B. undatum* can be approximately 5 times greater than those reported in this study when food odour is detected. The length of time that *B. undatum* can maintain this higher ‘feeding speed’ and under what circumstances they choose to employ this increased movement is unclear, but there may be a link to the intensity and type of food odour. Fishermen maintain that CPUE is higher when *Cancer pagarus* is used as a component of the bait; perhaps *B. undatum* alter their movement energy expenditure selectively, according to species-specific odour cues. This has been suggested by Evans et al. (1996), who found that *B. undatum* moved at the greatest speeds towards the carrion of swimming crabs, *Liocarcinus depurator* (L.), compared to purple heart urchins, *Spatangus purpureus* (Müller, O. F., 1776), and pouting, *Trisopterus minutus* (L.). The low movement speeds of *B. undatum* lead to potentially vulnerable, isolated sub-populations (Weetman et al., 2006) and could reduce the ability of *B. undatum* to move away from disturbance caused by the construction of wind turbines in the current study area.

5.1.6 Valuation of the windfarm area for lease

The valuation of the *B. undatum* fishery in the windfarm AfL, east of the Isle of Man, derived from density estimates produced by this study, is £3.99 million. Due to the relatively low recapture rates of tagged individuals during the Lincoln-Peterson surveys, there are relatively large 95% confidence intervals (£2.72 million– £6.28 million). Confidence intervals would be reduced,
providing a more precise valuation, with greater recaptures in the Lincoln-Peterson survey. Suggestions for future methodologies are found in section 5.3. Whilst the precise value of the *B. undatum* fishery could not be obtained in this study, it is now clear that the *B. undatum* fishery in the windfarm AfL has significant economic value. This valuation describes the existing *B. undatum* stock, of course with sustainable levels of fishing and responsible management of the fishery, stocks should be naturally replenished, providing greater cumulative value over time. Based on these results, it is now important to carefully consider what the potential effects of the proposed windfarm could be on the existing *B. undatum* fishery, both in the construction and operational phases of the development. There will certainly be displacement of the fishery during construction, as the creation of a safety exclusion zone around the building work will be required (Blyth-Skyrme, 2010). This displacement can lead to increased competition and conflict in other areas (Mackinson *et al.*, 2006). Once construction is complete, there is evidence that the windfarm may provide some benefits to potting fisherman. Trawling vessels tend to avoid the confined areas between turbines, which means that potting fishers can be provided with a ‘safe-haven’, where the risk of their fishing gear being damaged/removed by trawling vessels is eliminated (Blyth-Skyrme, 2010). Perhaps the greatest area of concern is the potential mortality of *B. undatum* during the construction phase. It is possible that suspended sediment created during construction could smother less mobile organisms such as *B. undatum*. There could also be longer-term changes in sediment dynamics and benthic community composition, which could have unpredictable effects on the *B. undatum* population. There is a need for further research into the response of pot fishery species to offshore windfarm construction and operation, particularly any long-term effects that may occur. This would allow for an evidence-based assessment of the level of impact that specific fishery species could experience as a result of the development.

5.2 Laboratory analyses

5.2.1 Total shell length distribution

*B. undatum* were larger in the windfarm AfL, east Isle of Man in 2016 (mean TSL = 97.0 ± 0.3 mm) than in Ramsey Bay, east Isle of Man in 2015 (mean TSL = 90.3 ± 0.5 mm) (Robinson, 2015). Migration direction of *B. undatum* has been shown to be asymmetrical in British waters, with the majority of migration occurring in an inshore to offshore direction (Weetman *et al.*, 2006). As the windfarm AfL is further offshore than Ramsey Bay, it could be the case that the population is made up of older larger individuals. The lower end of the TSL distribution in the windfarm AfL was truncated in comparison to Ramsey Bay (Robinson, 2015), further suggesting that younger, smaller *B. undatum* may be more abundant in inshore areas. The percentage of *B. undatum* below the MLS of 70mm in the non-riddled samples in this study was 1.27%, so the current MLS (70mm) in the IOM is not causing significant reductions in landings in the windfarm AfL. It is commonly reported
that *B. undatum* population characteristics vary over small spatial scales. For example, Shelmerdine *et al.* (2007) reported a significant difference in TSL between *B. undatum* populations on the eastern and western sides of Shetland, Scotland. The difference in TSL distributions between Ramsey Bay and the windfarm AfL suggests that localised sub-populations of *B. undatum* with differing population characteristics may be present in Isle of Man waters.

5.2.2 Maturity

The size at sexual maturity (SAM), for fishery management purposes, is defined as the size at which 50% of a population is sexually mature (King, 2007). The total shell length at 50% maturity (L\textsubscript{50}) in the windfarm AfL was different for male and female *B. undatum*. Based on visual assessment of the gonads, female L\textsubscript{50} was 69.8 mm and male L\textsubscript{50} was 83.9 mm. These results give *B. undatum* from the windfarm AfL, east of the Isle of Man, the 2\textsuperscript{nd} highest L\textsubscript{50} values of currently published literature, with only the Shetland Islands having greater L\textsubscript{50} values (Table 9). The literature surrounding *B. undatum* SAM shows mixed results, with some studies reporting a greater L\textsubscript{50} in males, whilst others report greater L\textsubscript{50} values in females (Table 9). This variation in L\textsubscript{50} according to location is unsurprising, as the limited larval dispersal and adult movement of *B. undatum* leads to genetically isolated subpopulations, even over distances of 1 – 2km (Weetman *et al.*, 2006; Pálsson *et al.*, 2014). The mechanisms responsible for driving the differentiation in SAM between *B. undatum* populations are currently unknown. A relationship between SAM, mortality and growth rates has been suggested in a number of species (Stearns & Koella, 1986). Mortality and growth rates will vary according to a number of factors, such as fishing pressure, predation, parasitism, food availability and habitat suitability (Haig *et al.*, 2015). There is also a range of abiotic variables such as temperature and salinity that have been shown to have an effect on the mortality and growth rates of gastropods (Montory *et al.*, 2014). It should also be noted that a wide range of methodologies have been used to assess *B. undatum* maturity (Table 9), which makes meaningful comparisons between different studies difficult. As *B. undatum* has an annual breeding cycle (Kideys *et al.*, 1993; Valentinsson, 2002), the visual appearance of the gonads is likely to alter depending on the time of year that sampling occurs, further contributing to the variation in L\textsubscript{50} values produced by different studies. A move towards a standardised *B. undatum* maturity assessment methodology and sampling time would assist with the comparability of future *B. undatum* stock assessments. This study used similar maturity assessment methodology to Haig *et al.* (2015), who also found higher L\textsubscript{50} values in male *B. undatum* in Welsh territorial waters, although the L\textsubscript{50} values in Wales were lower than this study for both sexes (Table 9).

An iterative search procedure for the inflection point of penis length produced a highly similar value to the L\textsubscript{50} from visual assessment of male gonads (morphometric inflection = 83.9mm TSL;
This suggests that there is an increase in the rate of penis growth that closely coincides with the onset of sexual maturity in male *B. undatum*. The iterative search procedure is therefore a viable method of determining sexual maturity in males, a conclusion also reached by McIntyre (2015). This method may be useful if sampling occurs during times in the breeding season when male gonad differentiation is unclear, for example immediately after spawning when male gonads are ‘spent’ (Haig *et al.* 2015).

Based on the results of this study, it appears that the Isle of Man MLS of 70mm TSL is currently appropriate for females ($L_{50} = 69.8$mm TSL) but not for males ($L_{50} = 83.9$mm TSL) in the windfarm AfL. Before any decisions regarding alterations to the Isle of Man MLS for *B. undatum* are made, it is important to gain a complete picture of how SAM varies in different areas of the Isle of Man’s territorial waters, as based on current literature (Table 9), SAM is likely to vary over relatively small spatial scales. An overall increase in MLS may disproportionately impact fishermen in other areas of the Isle of Man who fish *B. undatum* with smaller $L_{50}$ values. Whilst a regional MLS approach may be found to be the most appropriate, this would introduce additional challenges in terms of enforcement. As DEFA is moving towards a more complete picture of *B. undatum* populations surrounding the island (J. Emmerson pers. comm., July 2016), a discussion of the options surrounding regional management of *B. undatum* will be possible in the near future.

### 5.2.3 Length-Weight relationship

Male and female *B. undatum* in the windfarm AfL have significantly different length-weight relationships. Males have a higher weight for a given TSL than females, but this difference only becomes apparent at greater TSL values. The $b$ value in the relationship $W = aL^b$ can be interpreted as describing the type of allometric growth displayed by the animal (King, 2007). The $b$ value for males is 3.37 suggesting positive allometric growth, whilst 2.78 for females suggests negative allometric growth. Male *B. undatum* therefore appear to invest more energy into weight gain, whilst females favour investment into TSL growth. The large size of the mature male penis in proportion to the rest of the body could explain these results, as the iterative search procedure on male penis length found a rapid expansion occurring at 83.9mm TSL (see section 5.2.2). This would explain the difference in weight for a given TSL between sexes only occurring at higher TSL values. The results produced by this study are atypical when compared to studies carried out in France, which found no difference in the length-weight relationship between sexes, with all *B. undatum* showing negative allometric growth (investing more energy into shell length growth than weight increase) (Santarelli and Gros, 1985; Heude-Berthelin *et al.*, 2011). The findings of this study merit further investigation with larger sample sizes.
5.3 Recommendations for future methodologies

The current study was able to produce estimates of abundance and monetary value of the *B. undatum* stock within the windfarm AfL. It was also the first of its kind to produce estimates of *B. undatum* population size using Lincoln-Peterson mark-recapture methodology in restricted sample boxes, in order to remove issues surrounding standardisation of fishing effort and location experienced by previous studies (See section 5.1.4). This trial of novel methodology has also provided insights into potential refinements and alternatives to the methodology used, which could achieve greater precision and accuracy in future abundance assessments of slow moving benthic organisms such as *B. undatum*. These refinements and alternatives are as follows:

5.3.1 CPUE Depletion

An alternative to the currently used Lincoln-Peterson methodology for determining *B. undatum* population size is the use of a CPUE depletion model. A CPUE depletion survey is used to estimate the abundance of a population at $t_0$ (the beginning of the experiment). This is achieved by repeatedly fishing a defined area and analysing the reduction in CPUE over time (Ricker, 1975). The accuracy of this methodology is dependent on a number of assumptions:

1. The population is closed
2. The probability of each individual being caught in a trap is constant throughout the experiment
3. All individuals have the same probability of being caught

Due to the slow movement speeds of *B. undatum* (9.31 m day$^{-1}$ in this study), it would be possible to utilise a relatively small sampling area, for example a 200 x 200m box (40,000 m$^2$), and carry out an intensive 1 – 2 week long depletion survey, whilst still meeting the assumption of a closed population. Based on abundance estimates produced in this study, a 200 x 200m area would give an initial population abundance of approximately 8,000 *B. undatum*, with an approximate weight of 755 kg. If 100 pots were used in the survey, based on the CPUE in this study (2.94 kg pot$^{-1}$), there would be an initial catch of 294 kg, leaving 461 kg remaining in the sample area. This reduction of population size would be large enough to detect a reduction in CPUE within a week of repeated sampling. This procedure should be repeated at multiple sample locations to provide an average abundance estimate for the entire area of interest. As *B. undatum* density is known to vary over relatively small spatial scales (Table 8), to ensure that sampling effort is appropriate and feasible, it would be advisable to carry out a small pilot survey in the area of interest if approximate *B. undatum* densities and CPUE are unknown.
The data required for the CPUE depletion model are as follows (Ricker, 1975; Krebs, 2014):

- \( C_i \) = Catch (number of individuals or weight) removed at sample time \( i \)
- \( K_i \) = Accumulated catch from the start of experiment up to the beginning of sample time \( i \)
- \( f_i \) = Amount of trapping effort expended in sample time \( i \) (number of pots fished)
- \( F_i \) = Accumulated amount of trapping effort (number of pots fished) from the start up to the beginning of time \( i \)

If all the assumptions are met, CPUE will be directly proportional to population size, and the initial population size at \( t_0 \) can be calculated using a linear regression of the relationship between CPUE (\( C_i \)) and accumulated catch (\( K_i \)).

There would be a number of advantages to this method:

- No tagging required, reducing the man hours required at sea
- Removal of issues related to non-random mixing of tagged *B. undatum* with the wider population (clumping)
- Simple methodology – easily replicable

One disadvantage of this method, if used in fishery-dependent surveys, is that fishermen may be reluctant to use their own gear to fish an area repeatedly whilst receiving diminishing returns. For this reason, it would probably be necessary to invest in a number of whelk pots, which collaborating fishermen would then be asked to fish.

### 5.3.2 Modification of current Lincoln-Peterson methodology

#### 5.3.2.1 Use of the desired coefficient of variation to determine appropriate sizes of sample areas

This study has used Lincoln-Peterson mark-recapture methodology to produce estimates of *B. undatum* density in an area with no previously published density data. Based on these estimates, and personal observations during the sampling procedure, there are a number of potential refinements to the methodology that could lead to increased recapture rates, and subsequently reduced confidence intervals for abundance estimates in the windfarm AfL and elsewhere. To achieve greater recapture rates, either the sample area must be reduced in size or more *B. undatum* must be marked and released. An increase in tagging effort would be more expensive as it would require more boat time. Therefore it is recommended that future studies following this mark-recapture methodology modify the size of the sample area to complement the number of *B. undatum* they are able to tag. In this study it was possible for 3 people to tag approximately 1000 *B.*
undatum in a day. Future studies could use a coefficient of variation formula outlined by Seber (1982) alongside approximate estimations of population size in order to determine the appropriate size for sample areas. The coefficient of variation (CV) equation for Lincoln-Peterson estimates is as follows (Seber, 1982):

\[
CV(N) \equiv \frac{1}{\sqrt{R}} = \frac{1}{\sqrt{MC/N}}
\]

Where:
- \( R \) = Expected numbers of tagged individuals to be caught in the recapture phase of the Lincoln-Peterson survey
- \( M \) = Number of individuals tagged and released
- \( C \) = Total number of individuals caught in the recapture phase of the Lincoln-Peterson survey
- \( N \) = estimated population size
- \( CV(N) \) = Coefficient of variation of estimated population size

The \( CV \) for population estimates is approximately half of the relative estimate precision (Krebs, 2014), so for an abundance estimate with a precision of \( \pm 10\% \), a \( CV \) of 0.05 is required. Based on the mean density (0.2 m\(^2\)) produced by this study, in a sample area of 200 x 200m, \( B. \) undatum abundance would be approximately 8000. If 1000 individuals were marked and released, we can solve the above equation for \( C \), giving:

\[
C = \frac{N}{(M)(CV(N))^2} = \frac{8000}{(1000)(0.05^2)} = 3200
\]

So a total recapture of 3200 individuals would be required for an abundance estimate with a \( \pm 10\% \) precision in a 200 x 200m sample area in the windfarm AfL. The approximate weight of a single individual can be calculated by dividing the weight of a full whelk sack by the mean number of individuals in a full whelk sack:

\[
\frac{\text{full sack weight}}{\text{number of individuals per full sack}} = \frac{38}{402.6} = 0.0944 \text{kg}
\]
Based on a CPUE of 0.20 kg pot\(^{-1}\) produced by this study, approximately 103 pots would have to be hauled to recapture 3200 individuals. This level of effort could reasonably be achieved within a single day of fishing. With a \(CV(N)\) of 0.05, the number of recaptured tagged \(B.\ undatum\) would be:

\[
R = \frac{1}{0.05^2} = 400
\]

Lines of pots should be spaced equally in a ‘grid formation’ to ensure equal capture probabilities for all individuals within the sample area. This procedure could then be repeated in a number of randomly located 200 x 200m boxes within an area of interest to produce mean abundance estimates. If future studies employ this coefficient of variation method to determine appropriate sizes for sample areas, based on general approximations of expected population size and CPUE, they should be prepared to allow for greater recapture effort than is required by the estimated value of \(C\), as a conservative measure.

5.3.2.2 Separate studies of movement and abundance

This study was able to estimate both abundance and movement speeds using a single survey, by tagging each marked \(B.\ undatum\) in the Lincoln-Peterson survey with a unique identification code and recording the GPS locations of release and recapture. However, this methodology may have caused issues with regard to the random mixing of tagged \(B.\ undatum\) with the wider population (an assumption of the Lincoln-Peterson index). In order to record precise GPS coordinates of release locations, tagged \(B.\ undatum\) with known identification numbers were lowered to the seafloor in batches of 100, in a similar way to Robson (2014) and Robinson (2015). Movement speeds of \(B.\ undatum\) are low and it is unknown to what extent movement direction is random. For this reason it could be possible that tagged \(B.\ undatum\) were ‘clumped’ and not randomly mixed with the population in the 1km\(^2\) sample boxes. This is supported by the fact that many of the strings fished within the sample boxes had no recaptures of marked individuals, despite reasonable catches of unmarked animals, whilst one string located nearby a concentrated area of release points in study area B had more recaptures. One method of increasing random mixing of tagged \(B.\ undatum\) in the population would be to increase the initial spread of individuals at release. This could be achieved by releasing marked animals with a more ‘scattered’ approach, perhaps by continuously pouring marked animals out of a basket as the research vessel steams along transects of the sample area.

Whilst this would provide a greater initial spread of marked animals, it would make analysis of \(B.\ undatum\) movement impossible, as this requires precise GPS coordinates of release for each marked individual. For this reason it is recommended that if a study of \(B.\ undatum\) movement is desired, it be carried out separately from the Lincoln-Peterson survey.
Table 9. Results from published literature for minimum landing size (MLS) and size at maturity (SAM) of *Buccinum undatum* using a range of methods and sampling months.

<table>
<thead>
<tr>
<th>Location</th>
<th>$L_{50}$ male</th>
<th>$L_{50}$ female</th>
<th>Method</th>
<th>Study period</th>
<th>MLS</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>England</td>
<td>46.4–76.2</td>
<td>44.8–77.8</td>
<td>Visual</td>
<td>Jan–Mar</td>
<td>45</td>
<td>Hancock and Urquhart (1959); McIntyre <em>et al.</em> (2015)</td>
</tr>
<tr>
<td>Ireland</td>
<td>63.2–83.2</td>
<td>–</td>
<td>PL</td>
<td>–</td>
<td>50</td>
<td>Fahy <em>et al.</em> (2000)</td>
</tr>
<tr>
<td>Shetland</td>
<td>86</td>
<td>101</td>
<td>–</td>
<td>–</td>
<td>75</td>
<td>Shelmerdine <em>et al.</em> (2007)</td>
</tr>
<tr>
<td>France</td>
<td>49</td>
<td>52</td>
<td>Histology</td>
<td>–</td>
<td>45</td>
<td>Heude-Berthelin <em>et al.</em> (2011)</td>
</tr>
<tr>
<td>Canada</td>
<td>49–76</td>
<td>60–81</td>
<td>PL/GSI</td>
<td>Apr and May</td>
<td>70</td>
<td>Gendron (1992); Santarelli (1985)</td>
</tr>
<tr>
<td>Iceland</td>
<td>45–75</td>
<td>-</td>
<td>PL</td>
<td>May and Sep</td>
<td>45</td>
<td>Gunnarsson and Einarsson (1995)</td>
</tr>
<tr>
<td>Sweden</td>
<td>53.5–71.9</td>
<td>51.5–71.5</td>
<td>Microscopy</td>
<td>Oct–Nov</td>
<td>45</td>
<td>Valentinsson <em>et al.</em> (1999)</td>
</tr>
<tr>
<td>Wales</td>
<td>57.9–74.8</td>
<td>57.5–66.5</td>
<td>Visual</td>
<td>Feb 2013 – May 2014</td>
<td>45</td>
<td>Haig <em>et al.</em> (2015)</td>
</tr>
<tr>
<td>Isle of Man</td>
<td>83.8 (PL)</td>
<td>69.8</td>
<td>Female: Visual</td>
<td>June – July 2016</td>
<td>70</td>
<td>Bolger (2016)</td>
</tr>
</tbody>
</table>

$L_{50}$ = length at which 50% of individuals are sexually mature (considered to be SAM). Methodology: Visual = visual assessment and grading of the differentiation of the digestive whorl; PL = penis length, considered mature when PL > 50% TSL; Histology = histological assessment of the gonad tissue; GSI = using the weight of the gonad relative to total weight as a gonadosomatic index; Microscopy = microscopic analysis for presence/absence of sperm/oocytes.
6. References


6.1 Grey literature


