Lagarosiphon Research Lough Corrib (LARC)

2018-2020
Final Report

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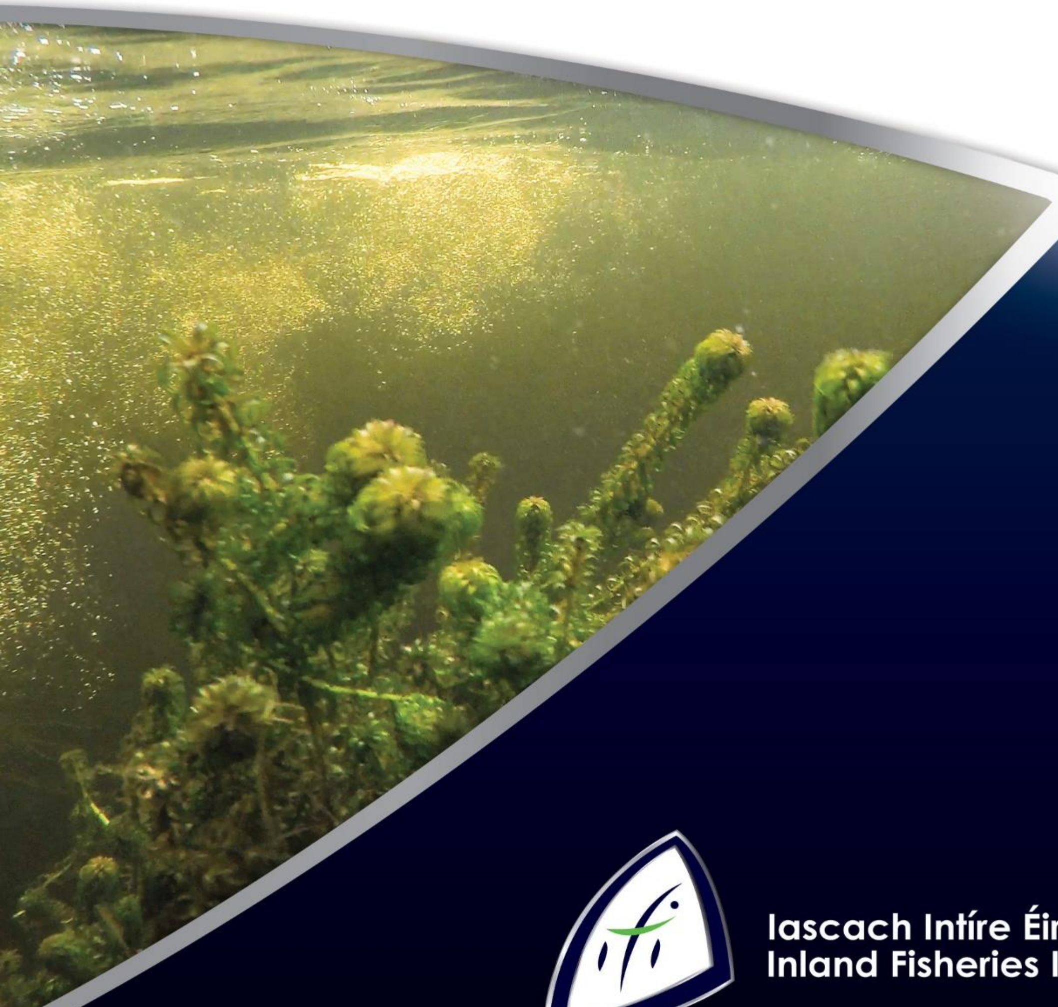

Iascach Intíre Éireann
Inland Fisheries Ireland

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Final Report

Inland Fisheries Ireland, 3044 Lake Drive, Citywest Business Campus, Dublin 24.

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LARC Project team

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List of keywords and abbreviations

CAISIE - Control of Aquatic Invasive Species and the Restoration of Natural Communities in Ireland
EPA - Environmental Protection Agency
ESA - European Space Agency
GIS - Geographic Information System
GPS - Global Positioning System
IAS - Invasive Alien Species
ICHEC - Irish Centre for High-End Computing
IDW - Inverse Distance Weighting
IFI - Inland Fisheries Ireland
LARC - Lagarosiphon Research Lough Corrib
NDVI - Normalized Difference Vegetation Index
NIR - Near-infrared
RGB - Red Green Blue
ROV - Remotely Operated Vehicle
SAC - Special Area of Conservation
SPA - Special Protection Area
UAV - Unmanned Aerial Vehicle
UVC - Ultraviolet-C

Executive Summary

Lagarosiphon major (Ridley) is an invasive aquatic species (IAS) of European Union Concern (EU Regulation 2016/1141) that was first recorded in Lough Corrib in 2005. Since that time Inland Fisheries Ireland (IFI), alongside partner agencies have been supporting extensive year-round control operations in the lake. An average area of 12.3 ha has been treated annually by the control team allowing native flora and fauna to re-establish at many sites since 2014. These treatments play a critical role in protecting the lake and preventing further spread.

The aim of the scientific research project (LARC 2018 to 2020) was to inform and support the on-going *L. major* management activities on Lough Corrib and provide up to date information on its distribution. This report summarises the remaining scientific work carried out by Inland Fisheries Ireland (IFI) during 2020 in work packages 2, 3 and 4. A general project (2018-2020) summary and recommendations are also provided in chapter 5.

WP2: Establish the current distribution and extent of colonisation of *L. major* in L. Corrib

Lake-wide *L. major* distribution results from four different sampling phases show that *L. major* progressed through a rapid range expansion when it was first introduced into Lough Corrib. Since 2010-2012, it has been spreading slowly towards the lower lake. Extensive sampling carried out in 2019 and 2020 revealed that there are still no records of *L. major* in the lower part of Lower Lough Corrib; however the southern edge of its distribution is approaching this boundary and growth is particularly good in some of the most southerly sites. During 2020 an estimated total of 12.3 ha of large *L. major* infestations (>50m^2) were present in five survey units. An additional ninety-eight relatively small (<50m^2) isolated patches were also recorded across ten survey units. A comparison with the 2013 distribution has shown that the area of infestation has decreased but the distribution has widened across the lake. At present, it appears that the annual control efforts undertaken on the lake are keeping the infestations at manageable levels and preventing the spread of the plant to the lower lake. However the lower lake area is continually at risk from infestation due to vector pathways.

- **WP3**: Determine the influence of habitat and environmental factors on *L. major* in L. Corrib

Data was gathered on macrophytes and a wide range of habitat and environmental variables (e.g. light, temperature, depth, substrate type) to investigate their influence on *L. major* in Lough Corrib at both local and lake-wide scales in 2019 and 2020. Analysis revealed that *L. major* presence was negatively affected by increasing depth and bottom hardness (i.e. was more likely to be found in shallow water with soft to medium bottom hardness); while fetch, slope, aspect and distance from shore were not found to be important. *L. major* abundance was also found to be affected by both CO_2 and light (i.e. higher abundance in areas with high CO_2 and low light levels) while temperature was not found to have a significant effect. The effects of CO_2 and light are newly documented by this study and provide new insights into why *L. major* is more abundant in certain areas.

- **WP4**: Develop and trial new approaches for surveying *L. major*.

A range of new approaches for surveying *L. major* in Lough Corrib were trialled between 2018 and 2020. Low-cost sonar with simultaneous ground truth sampling and recording using ArcGIS survey tools was identified as the most reliable and efficient survey method. It is also low-cost, has a low technology threshold, and provides a platform for the future development of satellite mapping.

The project also found that underwater imagery generated using a high-definition camera with live feed and geo-referencing ability was superior to grapnel sampling for ground truthing as the latter was biased towards certain species. UAVs proved useful for mapping *L. major* when the weed was at the surface in locations unsuitable for sonar surveys, for identifying jute matting locations and for assessing fragmentation from control methods. A pilot study to investigate the application of using Sentinel 2 multispectral satellite imagery to detect *L. major* in Lough Corrib at the lake-wide scale found that this method has potential for mapping the macrophyte at the lake-wide scale but more areal/polygon data (presence and absence of *L. major* and other common macrophyte species) is required to improve the algorithm and verify its usefulness. Electronic data collection forms were found to greatly increase the accuracy and efficiency of data collection. Suitable forms have been created and successfully tested for survey and management purposes.

1: Introduction

1.1 Background

Lagarosiphon major (Ridley) or Curly waterweed is an invasive aquatic species native to southern Africa that has invaded Lough Corrib. Invasive alien species (IAS) are defined as having been introduced accidentally or intentionally outside of their native geographical range(s) and where their introduction becomes problematic, damaging environments, economies or is detrimental to human health (IUCN, 2021). They are considered a major anthropogenic threat to global biodiversity, prompting efforts to enhance the effectiveness of invasive species management (e.g. Piria *et al*., 2017). In Ireland several IAS are listed under Part 4 - Regulation 49 and 50 of the European Communities (Birds and Natural Habitats) Regulations (S.I. No. 477 of 2011). Regulation 49 prohibits, except under licence, *the introduction or dispersal of certain species* including *L. major* and Regulation 50 makes it an offence *to or intend to import, buy, sell, breed transport and distribute listed animal or plant species or vector material*. Additionally the priority "Union list" of IAS came into force in 2016 (EU commissioning regulation 2016/1141). This list requires concerted action by Member States and includes *L. major*. Member States will be required to take measures to provide for (1) prevention, (2) early detection and rapid eradication of new invasions and (3) manage those species that are already widely spread in their territory (NPWS, 2016).

L. major has been spread across the globe by the horticulture trade and is now a destructive invader of watercourses across Europe, Australasia and the USA (Mitchell-Holland *et al.* 2018; Redekop *et al.,* 2016; Shaw *et al.,* 2016). The plant typically grows at depths less than 6 m and only the female plant is found outside of its natural range (Caffrey *et al.,* 2010; Nault and Mikulyuk, 2009). Therefore, in invaded systems, *L. major* reproduces and spreads via fragmentation, when pieces of the plant detach and float away (Redekop *et al.,* 2016).

L. major was first recorded in Lough Corrib in 2005 at Rinneroon Bay on the western shore of the upper lake (Caffrey and Acevedo, 2007). The plants invasive abilities were immediately evident with a 12 ha monoculture dominating the bay, blocking light to native plants and killing them. The dense canopy also closed the bay as an amenity to anglers and other water users (Caffrey and Acevedo, 2007). Within three years, *L. major* had spread to over 110 sites, covering 92 ha, effectively rendering large bays in the upper and middle lake, useless for amenity purposes (Caffrey *et al.,* 2011). Significantly, *L. major* has still not yet been recorded in the lower section of Lough Corrib (Morrissey *et al*., 2020) despite extensive areas being identified as high risk of colonisation due to its shallow nature (Caffrey *et al.,* 2011; Millane *et al.,* 2013; Morrissey *et al.,* 2020). Its most southerly distribution, however, had edged closer to this point by 2019 (Morrissey *et al*., 2020).

In response to the increasing threat of aquatic invasive species in Ireland, an EU LIFE+ nature and biodiversity project 'Control of Aquatic Invasive Species and Restoration of Natural Communities in Ireland' (CAISIE) commenced in January 2009 and was completed in January 2013. The CAISIE project developed and assessed *L. major* control methods while also monitoring the impacts of both *L. major* and control measures on the native biota (CAISIE 2013). Control methods trialled during the CAISIE project included a novel light exclusion technique (Caffrey *et al.,* 2010), mechanical cutting and harvesting, chemical control and hand-picking. Using these methods, the CAISIE control team removed this invasive weed from over 90% of the previously infested areas (CAISIE, 2013). Despite this, *L. major* expanded its range and the number of sites in need of maintenance increased. By September 2013, an area of 31.31 ha was considered in need of control measures (Millane *et al*., 2013).

Eradication of *L. major* is virtually impossible in a lake the size of Lough Corrib (16,631 ha, excluding islands) due to source banks (i.e. seeds and other material buried in the lake substrate) and ongoing reintroduction from various parts of the lake, but the on-going management efforts have so far buffered the locality from the potential socio-economic impacts. Today, efforts to manage and control *L. major* in Lough Corrib continue using the three principal methods (mechanical harvesting, light exclusion and hand-picking) developed during the CAISIE project (Geomara, 2016 and 2017; Oirbsean Ltd., 2018 and 2019; Morrissey *et al.,* 2020).

1.2 Project Aims

The aim of the LARC project (2018 to 2020) was to inform and support the on-going *L. major* management activities on Lough Corrib and to provide up to date knowledge on its distribution and new options for its monitoring and control. This project had five major work packages aiming to:

- WP1: Review the literature for recent developments in aquatic invasive aquatic plant species control which may inform L. major control measures
- WP2: Establish the current distribution and extent of colonisation of *L. major* in L. Corrib
- WP3: Determine the influence of habitat and environmental factors on *L. major* in L. Corrib
- WP4: Develop and trial new approaches for surveying *L. major*.

- WP5: Develop a concept design for semi-automated weed control

This report describes the scientific work carried out during 2020 and summarises the overall findings of the project. A series of recommendations are also presented. It is hoped that the data and knowledge acquired will inform the future management of *L. major* in Lough Corrib.

2: Develop and trial new approaches to surveying *Lagarosiphon major*

2.1 Introduction

Optimising the control and management of invasive species requires continual development of new methods that quantitatively map and monitor their spread (Ustin *et al.,* 2002). Traditional mapping and monitoring methods of macrophytes can be time and resource intensive. Modern technological solutions e.g. GIS based electronic data collection applications and remote sensing technologies such as satellite, aerial and underwater imagery and hydroacoustics/sonar (Cariveau *et al*., 2019, Jones *et al*., 2018, Stocks *et al*., 2019, Whyte *et al*., 2018, Zhou *et al*., 2018) are becoming increasingly affordable and may offer a more effective way to monitor many invasive aquatic species (IAS) over large areas in a shorter length of time. In contrast to traditional methods, many technologies can now provide real-time quantitative data, facilitating strategic management including early intervention and appropriate control method selection (Cariveau *et al*., 2019, Hunter *et al*., 2010). Despite the obvious advantages, the adoption of technological solutions can be inhibited or delayed by risk averse attitudes, insufficient financial and/or technical knowledge (Ghobakhloo *et al*., 2012) and legal limitations.

Traditional direct sampling methods generally involving quadrat or point sampling (e.g. direct observations, bathyscopes, grapnel sampling, scuba diving and snorkel-towing along pre-determined transect lines, marking infestations with handheld GPS units) used to survey *L. major* on Lough Corrib, while practical, are time consuming in large lakes and some may even carry a potential health and safety risk (Millane *et al.*, 2013; Stocks *et al*., 2019; Morrissey *et al*., 2020). These survey approaches provided point and line data enabling only a small proportion of the lake to be surveyed annually (Millane *et al.,* 2013). Since 2013, most *L. major* surveys in Lough Corrib have been conducted by the control team using visual observations in known problem areas or where recent sightings have been reported. This allows the team to simultaneously assess the infestation and measure site parameters. A disadvantage of this targeted approach is that large areas of the lake remain un-surveyed on an annual basis and sampling is not quantitative and in contrast to modern techniques such as some types of remote sensing they require return visits for up-to-date assessment.

This project has assessed the efficacy of various remote sensing methods to survey *L. major* in Lough Corrib. Remote sensing involves determining the physical characteristics of an area without making actual contact with the objects therein. However, ground-truth sampling is required to validate the results. The choice of remote sensing technique typically depends on the underlying question and method limitations. Aerial and underwater imagery (Yoklavich *et al*., 2015), sonar/hydroacoustics (Winfield *et al*., 2007; Stocks *et al*., 2019) and satellite (Free *et al*., 2020) imagery have been shown to be appropriate remote sensing techniques for sampling aquatic plants.

2.1.1 Aims and objectives

This work package aimed to develop and trial new approaches for surveying *L. major* on Lough Corrib. The work in 2020 built on the suite of technologies trialled in 2019 (Morrissey *et al*., 2020) and aimed to develop an integrated survey approach for assessing *L. major* in Lough Corrib.

During 2018 and 2019 the project team assessed the effectiveness of various remote sensing techniques, including underwater imagery, unmanned aerial vehicle (UAV) imagery, scientific echosounder (hydroacoustics) surveys and multispectral satellite imagery). Underwater imagery was found to be an effective tool for quantitatively sampling aquatic plants and substrate. The use of hydroacoustics, although weather dependent, was suited to surveying submerged stands of the plant but ground truthing (using direct observations, inspection of orthomosaic images, grapnel sampling, grabs, bathyscope and underwater imagery) was required; while UAVs were useful for mapping near shore areas and yielded better observational data in areas that were highly weeded and difficult to navigate with a boat. Multispectral imagery from UAV's and satellites provided similar spatial distribution and perimeter estimates (Morrissey *et al*., 2020).

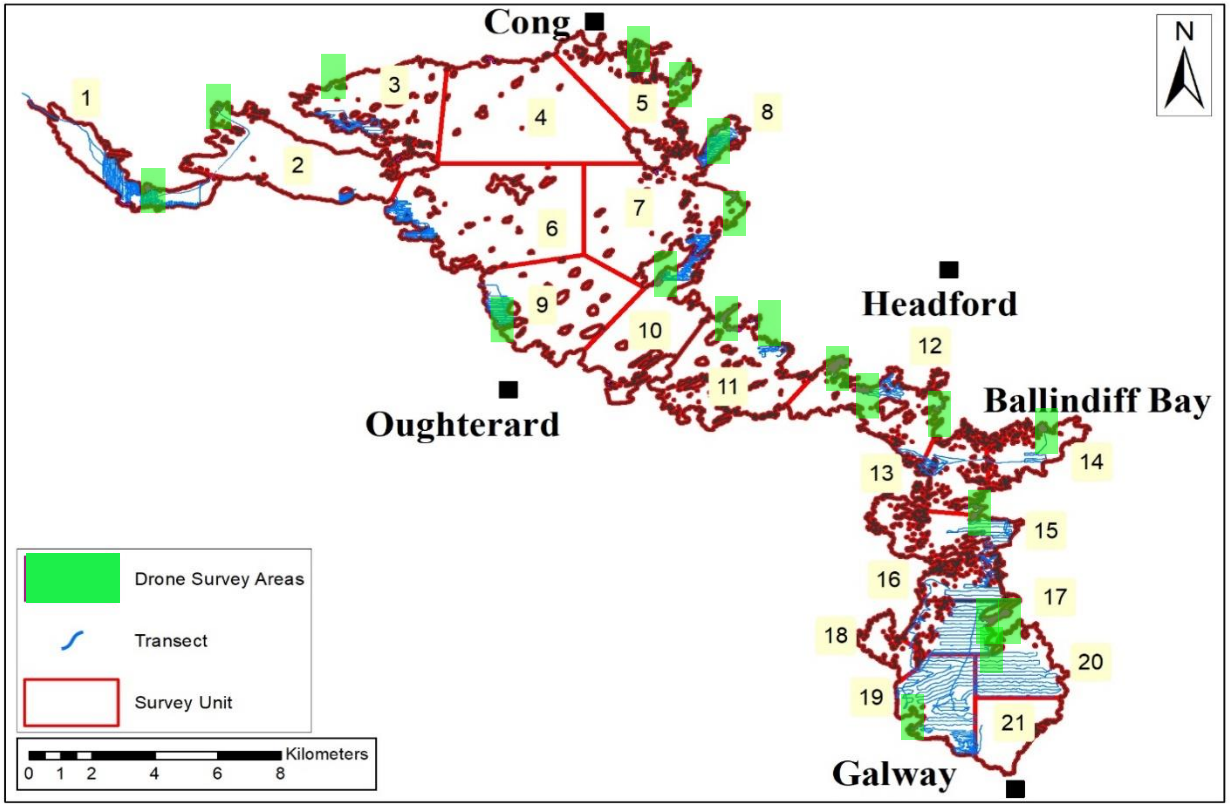
During 2020 the assessment of these technologies continued but was expanded to include the assessment of low-cost sonar equipment. Additionally a pilot study to assess the efficacy of using Sentinel 2 satellite data to detect *L. major* at the lake-wide scale was also initiated. The Irish Centre for High-End Computing (ICHEC) was commissioned to undertake this pilot study using IFI ground truth data as this work required computing power beyond the scope of the IFI ICT infrastructure.

2.2 Materials & methods

2.2.1 Study area and sampling period

To facilitate planning for the 2020 surveys the lake was divided into 21 survey units (Fig. 2.1). Survey units were assigned using the following criteria:

- Areas display similar physicochemical properties (based on data collected in 2019)
- Manageable size
- Proximity to launch sites/boat slips.



Survey Unit No.	Name
1	Maam/Drumsnauv
2	Shannawagh/Bob's Island
3	Doorus/Cornamona River
4	Cong
5	Lisloughrey
6	Rinneroon/Inchagoill
7	Ballycurrin
8	Ballynalty
9	Derrymoyle
10	Oughterard/Greenfields
11	Illaunfadda
12	Kilbeg
13	Opp. Ballindiff Bat
14	Ballindiff Bay
15	Annaghdown
16	Portarra
17	Curra
18	Moycullen Bay
19	Lower Lake west
20	Addergoole River
21	Clare River

Fig. 2.1. Lough Corrib survey unit boundaries are shown in red. Low-cost sonar transects are shown as blue parallel lines and UAV survey sites are represented by green rectangles.

2.2.2 Mapping *L. major* and its habitat using low-cost sonar

An extensive survey was carried out using a low-cost sonar unit (Lowrance Elite-7 Ti2 Row Active Imaging 3-in-1 Fishfinder) in 2020 (Fig. 2.1). The operational settings were: Fishing Mode = Shallow Water, Ping Rate = 15, Range = Auto, Down-imaging Frequency = 200 kHz, SideScan Frequency = 800 kHz and Wide Area Augmentation System (WAAS) = Enabled (Navico, 2019). The transducer was mounted at a 90° angle and boat speed was limited to <9km/h. Systematic parallel transects 40 m to 120 m apart were used. Spacing was determined for each survey unit based on existing knowledge of *L. major* distribution, with higher coverage in high-risk areas (Fig. 2.1). Ground-truth samples (n=2092) were collected concurrently using a grapnel hook or by visual observation to confirm the presence or absence of *L. major* at individual survey sites (Fig. 2.2). Ground-truthing sampling effort was higher in areas with diverse vegetation cover.

Down-imaging (200kHz) sonar data was processed for vegetation height (bioheight, m) and biovolume (%), water depth (m) and bottom hardness (dB) using online software (BioBase EcoSound (www.biobasemaps.com)). Vegetation detection was not possible at water depths <0.73 m. Biovolume (%), i.e. the average proportion of plant height to water depth was calculated. If biovolume was <5%, both bioheight and biovolume were recorded as zero (as per Navico, 2019). Bottom hardness (dB) was categorised as soft, medium or hard and was not reported where biovolume exceeded 60% (as per Navico, 2019). The data outputs were reviewed and erroneous water depths or biovolume were replaced with manually measured values. Data were imported into ArcMap 10.5 and maps were generated for bioheight (m), biovolume (%), bottom hardness (dB) and water depth (m) using the Inverse Distance Weighting (IDW) interpolation tool.

Side-scan (800 kHz) sonar data was reviewed in Sonar Viewer software for Lowrance (V.2.1.2) to investigate if it was possible to identify *L. major* in the echograms.

A binomial GLM was used to relate the probability of detecting (presence/absence) *L. major* with a grapnel hook to the recorded set of vegetation and environmental variables from sonar records. Survey unit was included in the model as a factor, to explore a possible effect of location in the lake.

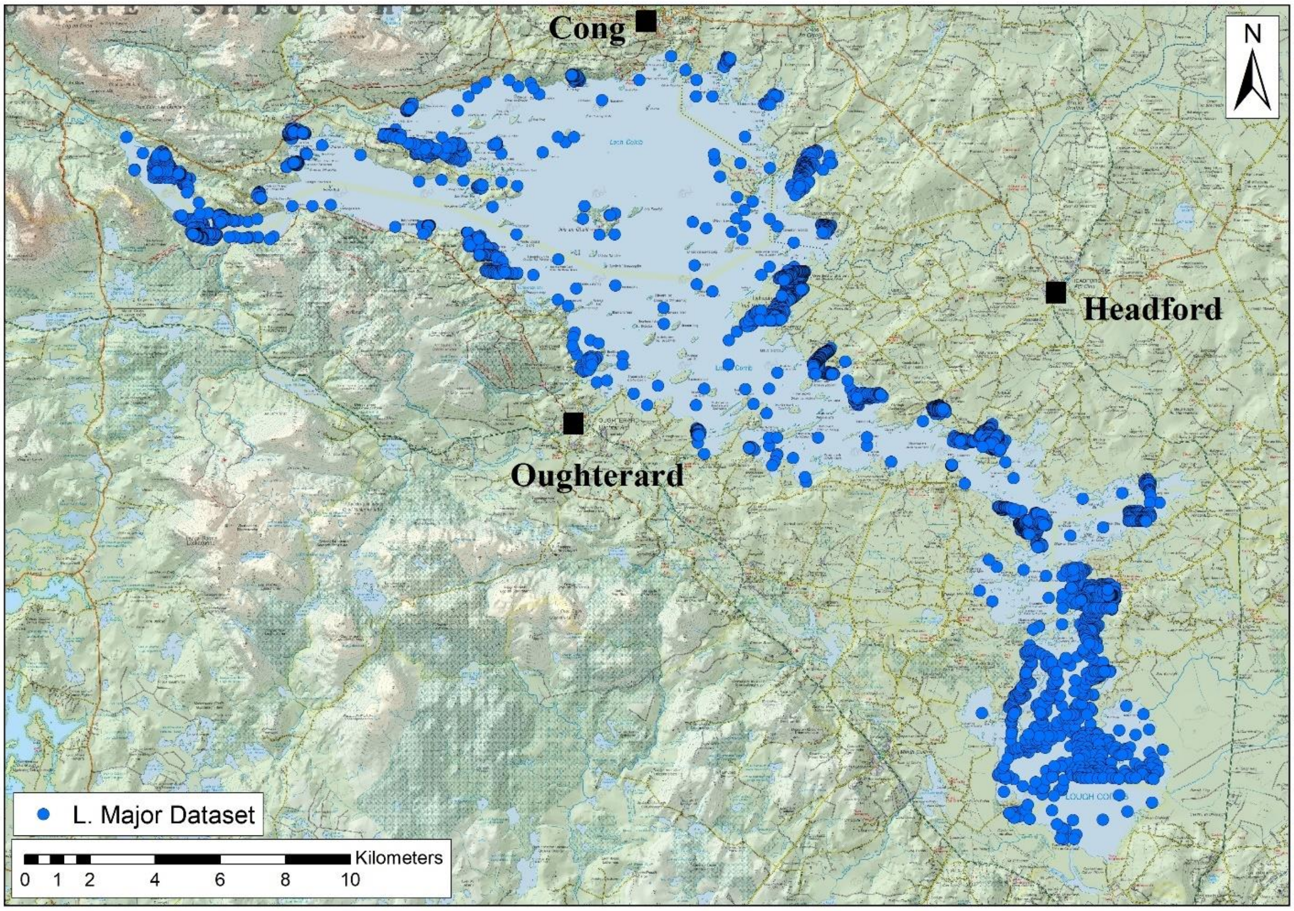


Fig. 2.2. Location of ground truth sampling sites for *L. major* in Lough Corrib 2019-2020.

2.2.3 Using unmanned aerial vehicles (UAV's) to survey *L. major*

Twenty-eight nearshore areas were surveyed with two UAV models (Fig. 2.1). Their in-built RGB cameras were used to capture images from altitudes of between 50-80 m. Automated (using DroneDeploy mapping software) and manual flights were flown. Orthomosaic images were generated using Drone2Map for ArcGIS and Pix4DReact software. To examine the effect of sampling season a UAV survey conducted in Clydagh Bay (SU12) on the 5th of February 2020 was repeated on the 8th of October 2020.

2.2.4 Mapping *L. major* using underwater imagery and grapnel sampling

The percentage cover (%cover) of common vegetation categories (*L. major*, Charophyte spp., *Myriophyllum* spp., *Potamogeton* spp., *Elodea canadensis*, *Fontinalis* spp., rosettes (e.g. *Isoetes* spp., *Lobelia* spp.) and reeds (e.g. *Phragmites* spp.)) were recorded at 200 sites (Fig. 2.2) between the 1st of

September 2019 and May 20th, 2020, using underwater cameras attached to a 1 m^2 steel quadrat. Vegetation presence/absence data were collected in parallel using a four-pronged grapnel hook.

A binomial model was used to investigate the agreement between the two sampling methods, i.e. the probability of detecting a macrophyte (presence/absence) by grapnel sampling and the percentage cover recorded by underwater imagery. This model included macrophytes (identified to species or family) and camera type as fixed effects (covariates) and sampling site as a random effect.

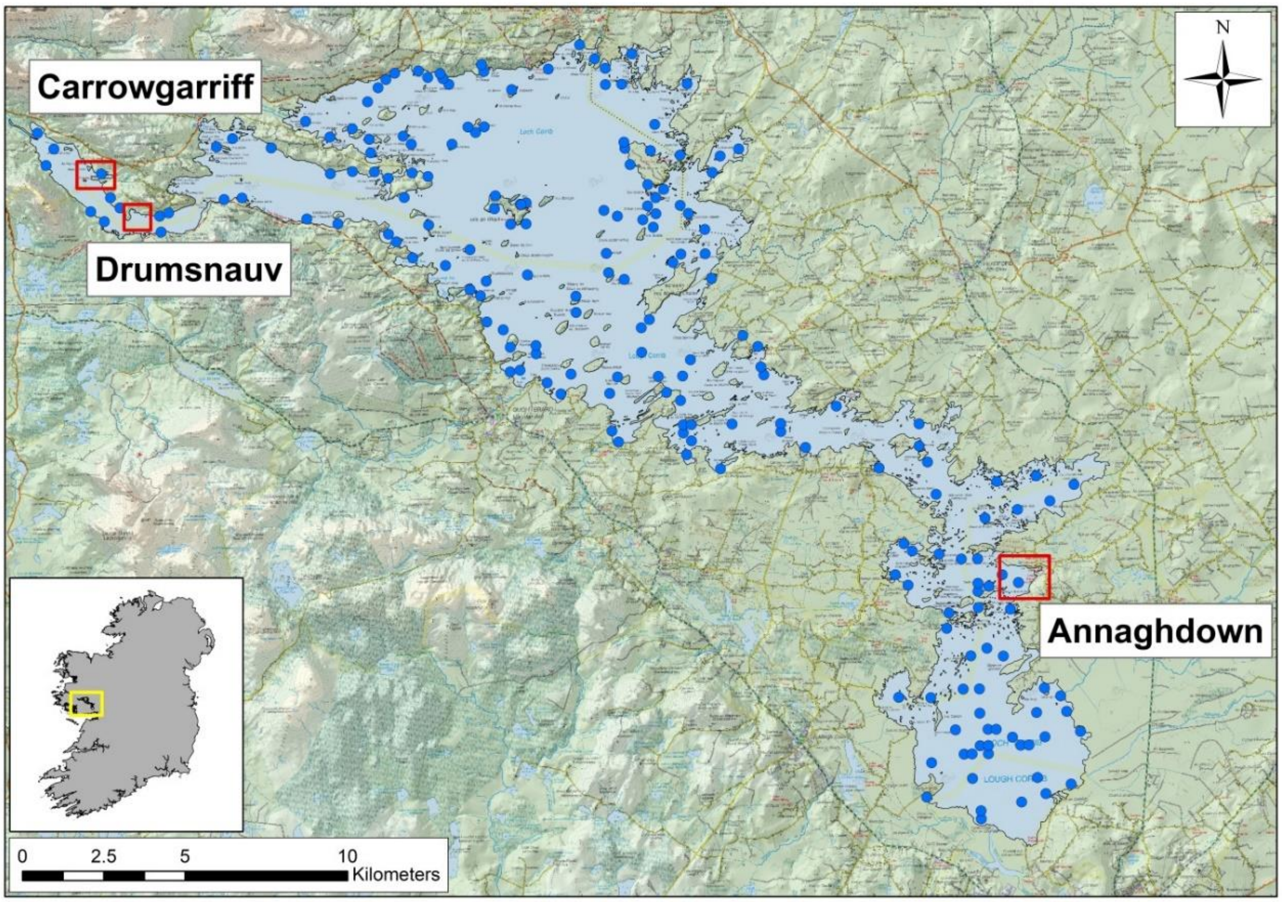


Fig. 2.3. Lough Corrib sampling sites 2019 to 2020. Lake-wide sampling sites using underwater imagery and grapnel sampling are represented by blue dots. (Additional satellite and scientific sonar (hydroacoustics) study areas are highlighted within red boxes).

2.2.5 Detecting *L. major* using multispectral satellite imagery at the lake-wide scale

The Irish Centre for High-End Computing (ICHEC) was commissioned to conduct a pilot study to investigate the efficacy of using Sentinel-2 multispectral satellite images for mapping *L. major* at the lake-wide scale. The main objective of the pilot study was to develop an algorithm for detecting *L. major* in Lough Corrib (Karki, 2020).

The methodology for developing the model was divided into three steps, (1) training, (2) model development and (3) application (Karki, 2020).

(1) Training dataset

An initial exploratory analysis was undertaken by ICHEC to determine which Sentinel 2 derived independent variables would best correspond to *L. major* percentage occurrence in Lough Corrib (Karki, 2020). The potential variables used and computation method were identified from published studies (Luo *et al*., 2016; Spears *et al*, 2016; Zhou *et al*., 2018; Morcillo-Pallarés *et al*., 2019; Stefanidis and Papastergiadou, 2019; Free *et al*., 2020) (Table 2.1). Indices and variables were computed using the European Space Agencies (ESA) open-source Sentinel Application Platform (SNAP) software (Version 6.0).

The training dataset was created by using polygon outlines and point locations for *L. major* in Lough Corrib collected during IFI field surveys in 2019 and cloud free Sentinel 2 scenes taken within two months of the field survey dates. For model training purposes the percentage occurrence of *L. major* (polygons and points) and computed independent variables were extracted at every 10m spacing (pixel resolution) for all the training areas. Low quality pixels (cloudy or near clouds) were removed from the analyses. Variables were also computed for additional locations where *L. major* was not recorded to ensure that the training dataset was unbiased and that the developed model is able to discriminate between the presence and absence of the invasive macrophyte (Karki, 2020).

Table 2.1. List of independent variables and their computation methods. The formula for the indices is adapted from Zhou *et al*. (2018).

Variables	Description	Formula/Source
NDVI	Normalized Difference Vegetation Index	(B8-B4)/(B8+B4) *B8 and B4 are reflectance for near-infrared (NIR) and red bands*
SAVI	Soil Adjusted Vegetation Index	(1+L) [(B8-B4)/ (B8+B4+L)] *Where L=0.5.* *B8 and B4 are reflectance for NIR and red bands*
NDAVI	Normalized Difference Aquatic Vegetation Index	(B8-B2)/ (B8+B2) *B8 and B2 are reflectance for NIR and blue bands*
WAVI	Water Adjusted Vegetation Index	(1+L) [(B8-B2)/ (B8+B2+L)] *where L=0.5.* *B8 and B2 are reflectance for NIR and blue bands*
CHL	Chlorophyll concentration (mg/m^3)	Computed using neural network based C2RCC Algorithm
TSM	Total suspended matter (g/m^3)	Computed using neural network based C2RCC Algorithm
B3	Normalized Water leaving reflectance (from green band B3)	Computed using neural network based C2RCC Algorithm

Note: C2RCC Algorithm= Case-2 Regional Coast Colour Algorithm (Brockmann *et al*., 2016)

(2) Model Development

An initial multivariate regression analysis was conducted to investigate if the inclusion of each candidate variable contributed significantly to the model (Karki, 2020). The regression included different combinations of input variables in a stepwise fashion, generating an optimized response variable based on several statistical criteria such as adjusted R-square value, Akaike information criterion (AIC; Yamashita *et al*., 2007), variance inflation factor (VIF; O' Brien, 2007), etc. A significance test was carried out during the regression analyses where values with a low P-value (<0.05) were considered significant for explaining the variance in the dependent variable. Different variables, for example different bands, were tested but only those found to be significant were short listed for inclusion during the model development as shown in Table 2.2. Different combinations of variables were tested iteratively to obtain the best fit within the predicted and observed values. A test of multicollinearity or redundancy was undertaken using variance inflation factor (VIF) where values higher than 7.5 were considered redundant (O' Brien, 2007). Following the test for multicollinearity TSM and NDAVI were dropped from further consideration as these did not improve the predictability of the model. The inclusion of the five variables, CHL, B3, NDVI, SAVI and WAVI gave the highest adjusted R^2 of 0.79 with a root mean square error (RMSE) of 0.01. Removal of any of these variables led to a decrease in R^2 value and increase in RMSE. The statistical analyses were carried out using Spatial Analyst extension available in ArcGIS 10.6.

Table 2.2 Summary of variable significance (higher % significance is highlighted in bold). The values of NDAVI and TSM are also shown although they were dropped in the final model.

Variable	% Significant	% Negative	% Positive
B3	100	**92.98**	7.02
NDVI	100	0.00	**100.00**
SAVI	100	45.61	**54.39**
NDAVI	96.49	19.30	**80.70**
CHL	94.74	19.30	**80.70**
WAVI	92.98	**52.63**	47.37
TSM	78.95	**87.72**	12.28

(3) Application

To validate model performance the model was applied to data that was not used during model development (Karki, 2020). Three relatively cloud free Sentinel 2 scenes (12/08 2019; 15/11/2019 and 17/12/2019) were selected and all five independent variables were calculated. The equation for the model was applied using the raster calculator function in ArcGIS to generate an image displaying predicted percentage occurrence of *L. major*.

2.2.6 Comparison of satellite imagery, sonar and ground-truth sampling

The efficacy of three methods; Sentinel-2 NDVI data, down-imaging sonar (both low-cost and scientific/hydroacoustics) and ground truth sampling, was compared for two areas (Annaghdown and Carrowgariff) where *L. major* occurred in Lough Corrib during 2019 (Table 2.3).

Table 2.3. List of surveys for satellite imagery, sonar (low-cost and scientific/hydroacoustics) and ground-truth sampling on Lough Corrib 2019

Study Area	Date	Method
Annaghdown	28/02/2019 - 01/03/2019	Scientific/Hydroacoustics
Annaghdown	12/03/2019	Sentinel-2
Annaghdown	28/02/2019, 01/03/2019	Ground truth: grab, grapnel
Carrowgarriff	27/08/2019	Low-cost sonar
Carrowgarriff	26/10/2019	Sentinel-2
Carrowgarriff	21-25/10/2019	Ground truth: grab, grapnel

Data from the three methods was overlayed with down-imaging sonar outputs, water depth, bottom hardness and bioheight in ArcScene 10.5 software.

In a first analysis, the relationship of Sentinel 2 NDVI data with bioheight and distance of vegetation from the surface were tested using Generalised Linear Models (GLM's). The candidate models included NDVI and bioheight, distance of vegetation from the surface and sampling site plus all interactions.

Secondly, the probability that vegetation of a given estimated bioheight was *L. major*, was investigated by comparing bioheight from sonar data to *L. major* presence/absence in ground-truth sampling data using the following GLM (LagPresAbs~Bioheight + Site) with a binomial distribution.

2.3 Results

2.3.1 Mapping *L. major* and its habitat using low-cost sonar

The efficacy of the low-cost sonar equipment to detect *L. major* was tested in survey units where the plant was present and absent. The probability of detecting *L. major* presence/absence using low-cost sonar was significantly affected by bioheight (GLM, $P < 0.05$), and survey unit (GLM, $P < 0.01$), such that the relationship between *L. major* presence and bioheight differed across the areas sampled (Fig. 2.4). *L. major* was not recorded as present when using the low-cost sonar equipment in sampling units SU9, SU11, SU12, SU14, SU16, SU17, SU19 and SU20.

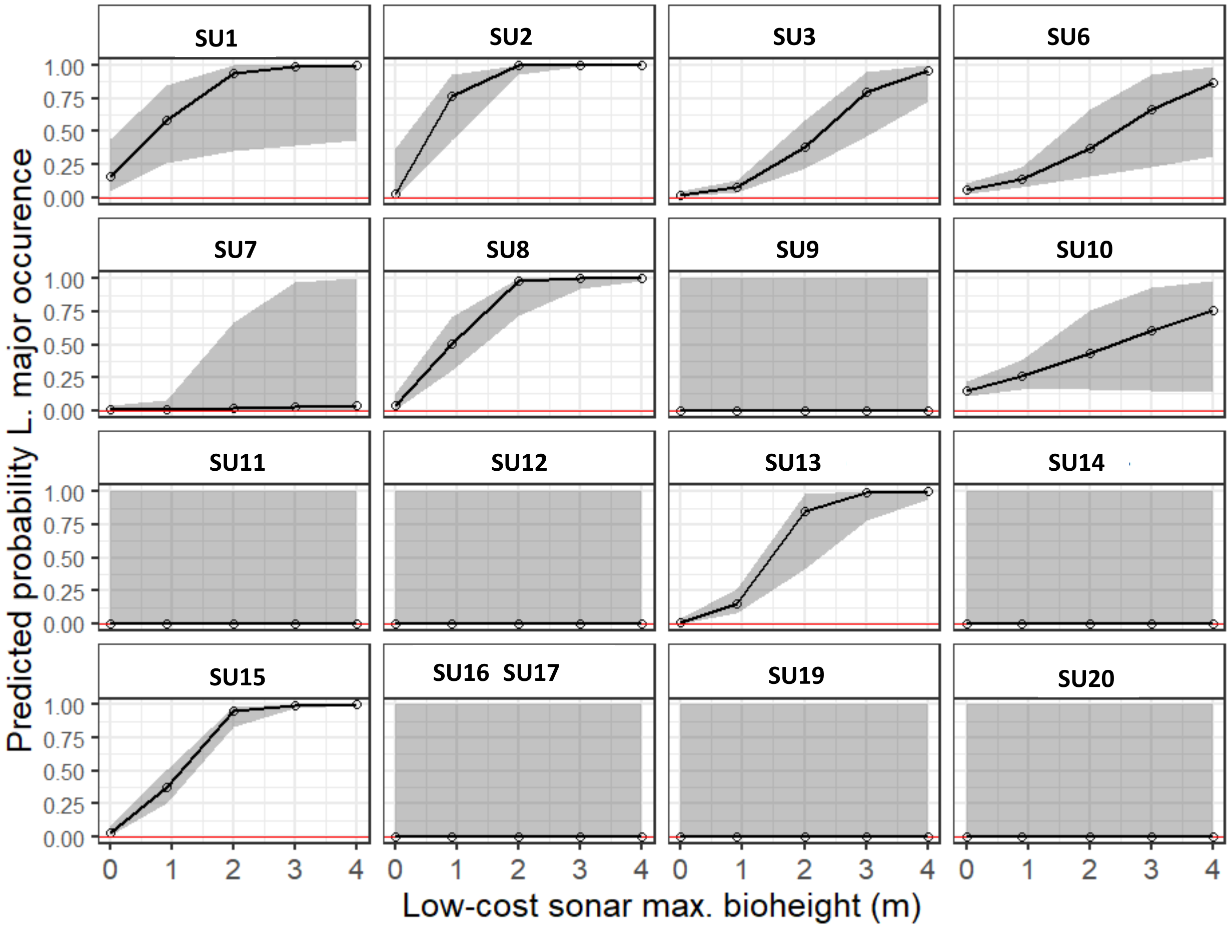


Fig. 2.4. The probability of *L. major* occurrence at a given bioheight (m) reported by low-cost across Lough Corrib survey units sampled in 2020.

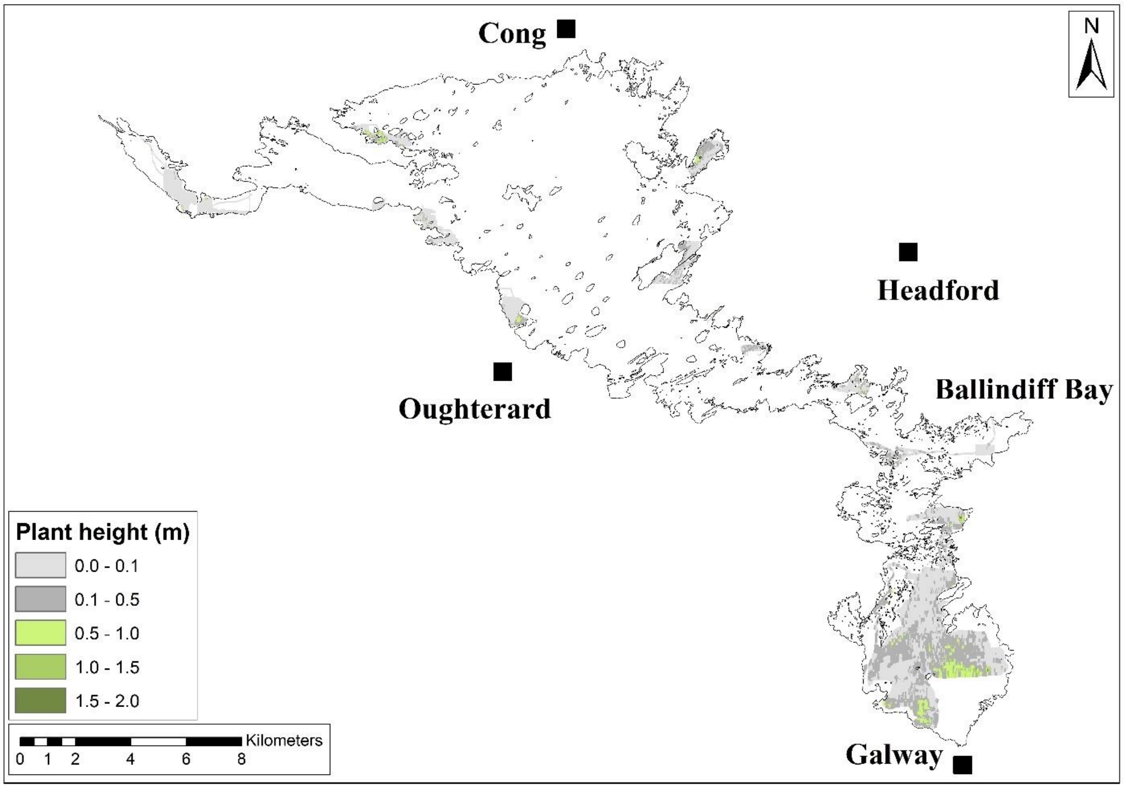


Fig. 2.5. Interpolated vegetation height (m) generated from low-cost sonar equipment deployed on Lough Corrib, 2020.

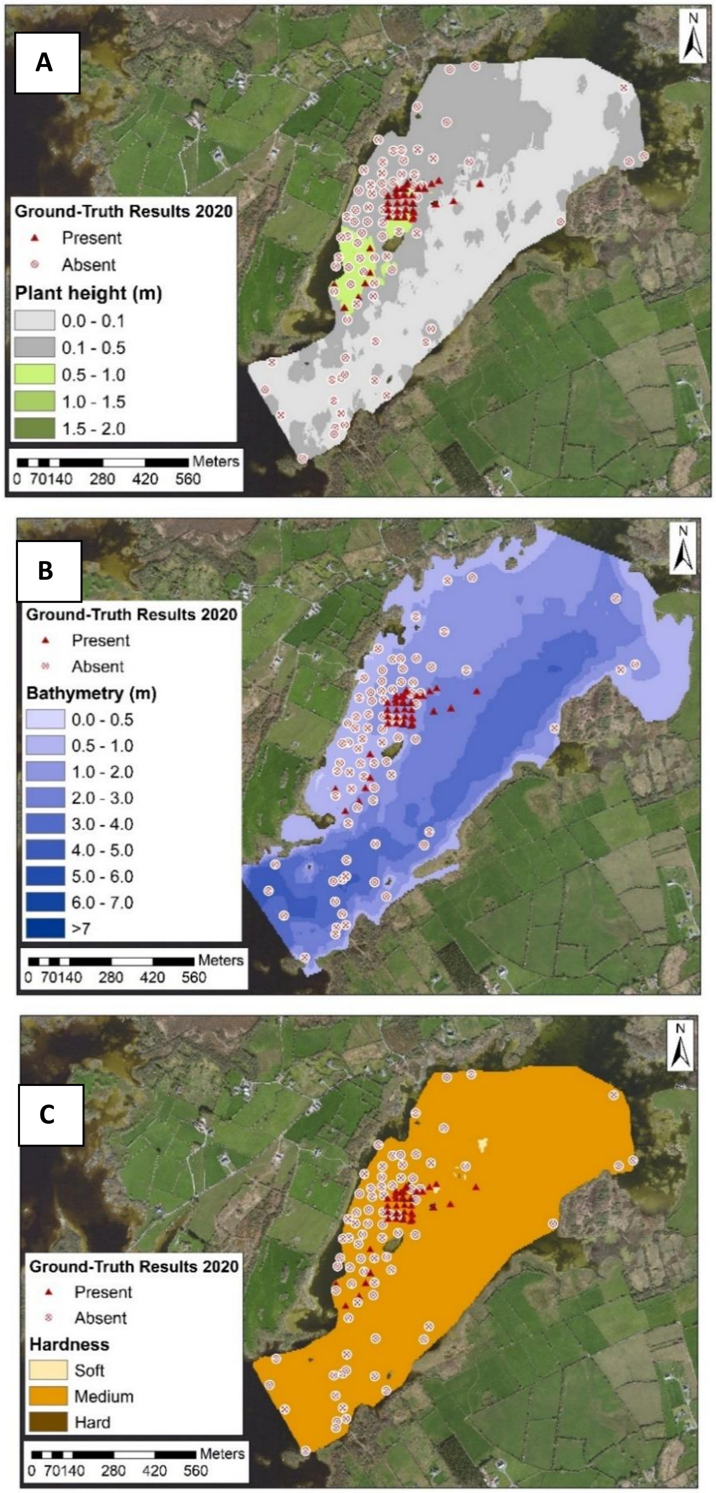


Fig. 2.6. Outputs from low-cost sonar surveys, (A) interpolated vegetation height (m), (B) water depth (bathymetry) (m) and (C) bottom hardness (dB) recorded at Ballynalty, Lough Corrib 2020. *L. major* ground-truth data is also shown.

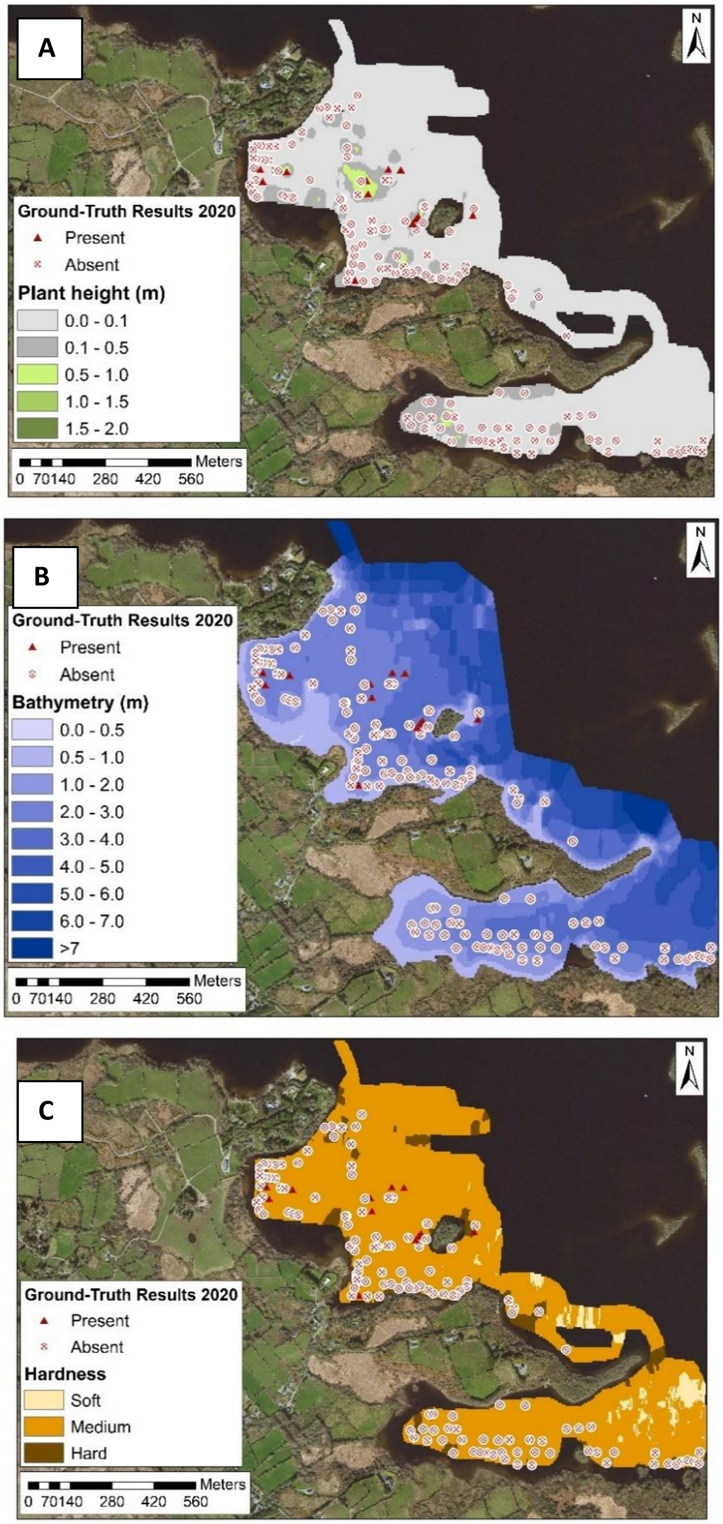


Fig. 2.7. Outputs from low-cost sonar surveys, (A) interpolated vegetation height (m), (B) water depth (bathymetry) (m) and (C) bottom hardness (dB), recorded at Rinneroon and Annaghbeg, Lough Corrib 2020. *L. major* ground-truth data is also shown.

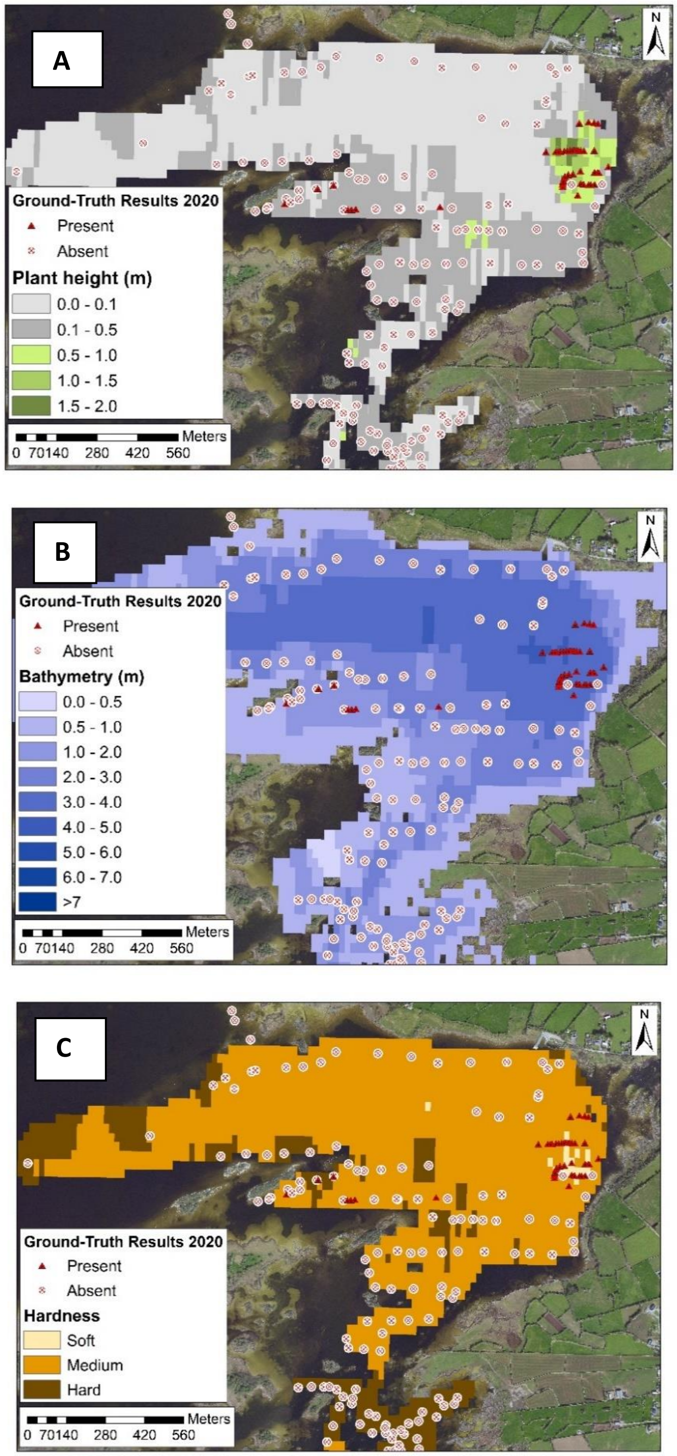


Fig.2.8. Outputs from low-cost sonar surveys, (A) Interpolated vegetation height (m), (B) water depth (bathymetry) (m) and (C) bottom hardness (Db) recorded at Annaghdown, Lough Corrib 2020. *L. major* ground-truth data is also shown.

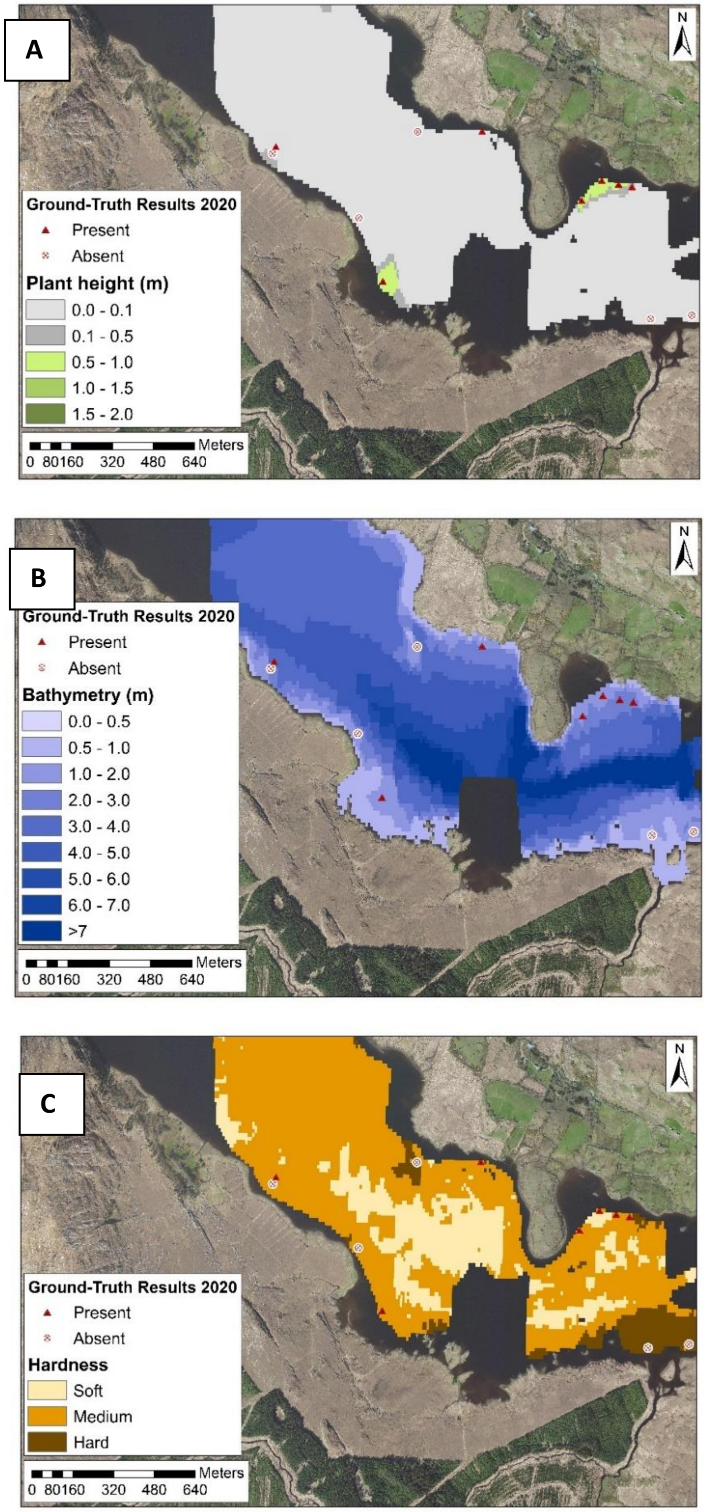


Fig. 2.9. Map outputs from low-cost sonar surveys (A) Interpolated vegetation height, (B) water depth (m) (bathymetry) and (C) bottom hardness recorded at Carrowgarriff/Drumsnauv, Lough Corrib 2020. *L. major* ground-truth data is also shown.

2.3.2 Using unmanned aerial vehicles (UAV's) to survey *L. major*

The UAV models tested in this study are primarily limited by their sampling range and the wet, windy weather that is typical for the west of Ireland. The operators found that lighting and water colour were highly variable and had an impact on orthomosaic image quality and results. UAVs were useful when quantifying weed that was at the surface and collecting data for jute mat locations and area covered (Fig. 2.10). A repeat survey of Clydagh Bay in February and October 2020 revealed that the ability to detect *L. major* and other macrophytes with UAV imagery was limited when vegetation was below the water's surface. Sampling season was also an important consideration (Fig. 2.11). This survey also demonstrated the need to ground truth the vegetation, using a lower altitude (higher resolution) sub-sample of the site.

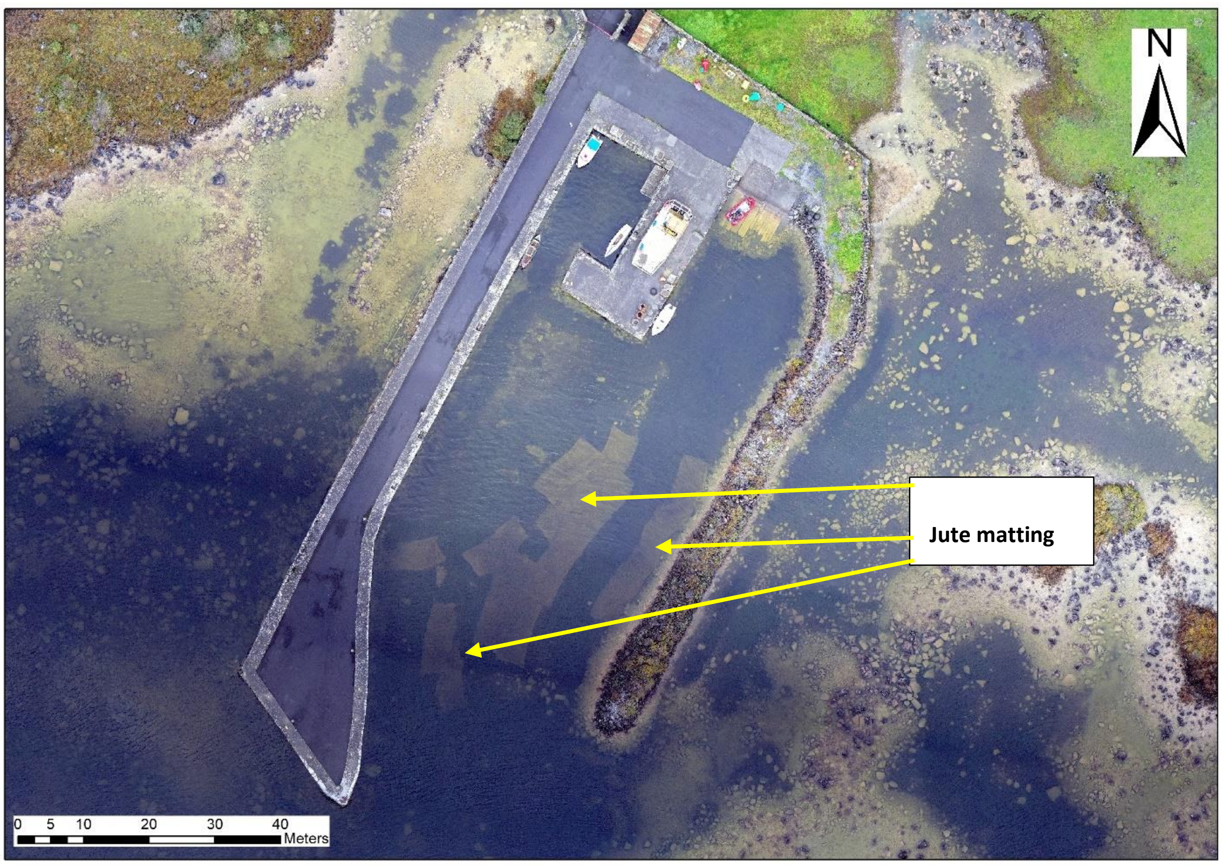


Fig. 2.10. UAV orthomosaic image showing jute matting in Kilbeg Pier, Lough Corrib, 7th October 2020.

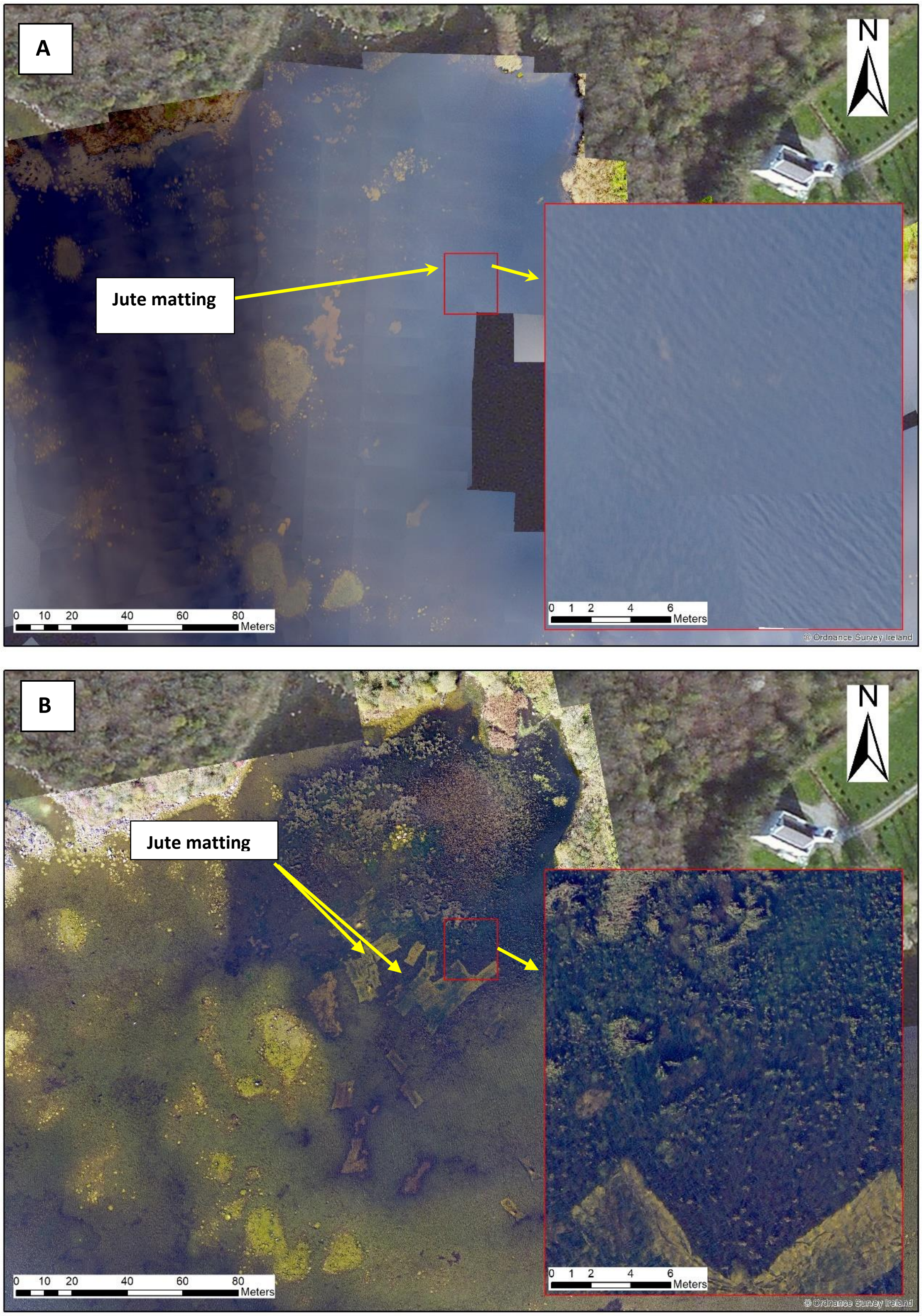


Fig. 2.11. Comparison of UAV orthomosaic images in Clydagh Lough Corrib (A) 5th February 2020 and B) 8th October 2020. Jute matting was more visible in October (image B).

2.3.3 Mapping *L. major* using underwater imagery and grapnel sampling

There was a significant positive linear relationship (LMM, P <0.001) between the observed distribution of macrophytes as reported by ground truth grapnel sampling (presence/absence) and percentage cover estimated from underwater imagery (Fig. 2.12), i.e. the higher percentage cover, the greater the chance of finding vegetation using a grapnel. There was typically a ~50% probability of observing a given macrophyte at a location where it had a percentage cover of 50% (Fig. 2.12). The type of macrophyte being sampled also had a significant effect (LMM, P <0.01) with charophyte species more likely to be detected by a grapnel than other macrophytes tested at a corresponding percentage cover. Camera model did not significantly affect the results (LMM, P >0.05).

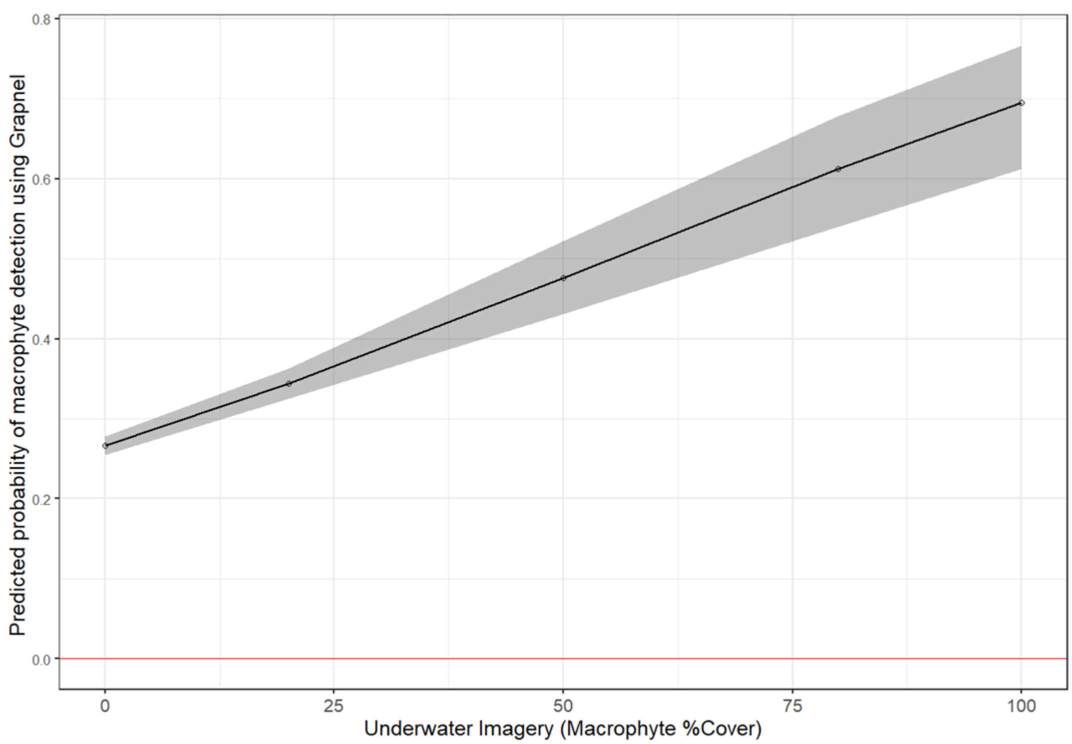


Fig. 2.12. Relationship between the observed distribution of macrophytes as reported by ground truth grapnel sampling (presence/absence) and underwater imagery (%Cover).

2.3.4 Detecting *L. major* using multispectral satellite imagery at the lake-wide scale

The multivariate regression model can be expressed as follows:

$$Response\ Variable = \lfloor \sum_{i=1}^{n} C_i x_i \rfloor + \lfloor C_0 \rfloor$$

Where Ci is the model coefficient for variables x1 and C_0 is the model bias. The equation generated can be expressed as:

L. major occurrence (%) = (207.41) – (10843.68 X B3) + (11.49 X CHL) + (1241.12 X NDVI) – (5444.11 X SAVI) + (706.35 X WAVI)

Combining the information from the multivariate regression equation and Table 2.2, it was evident that CHL and NDVI have mainly a positive correlation while B3 and SAVI have a predominantly negative relationship. WAVI shows a mixed relationship with negative significance slightly greater than the positive one.

The model was applied to the N=3 cloud free Sentinel 2 scenes from dates in August, November and December that were not used in the model development (see Figs 2.13 and 2.14 for examples).

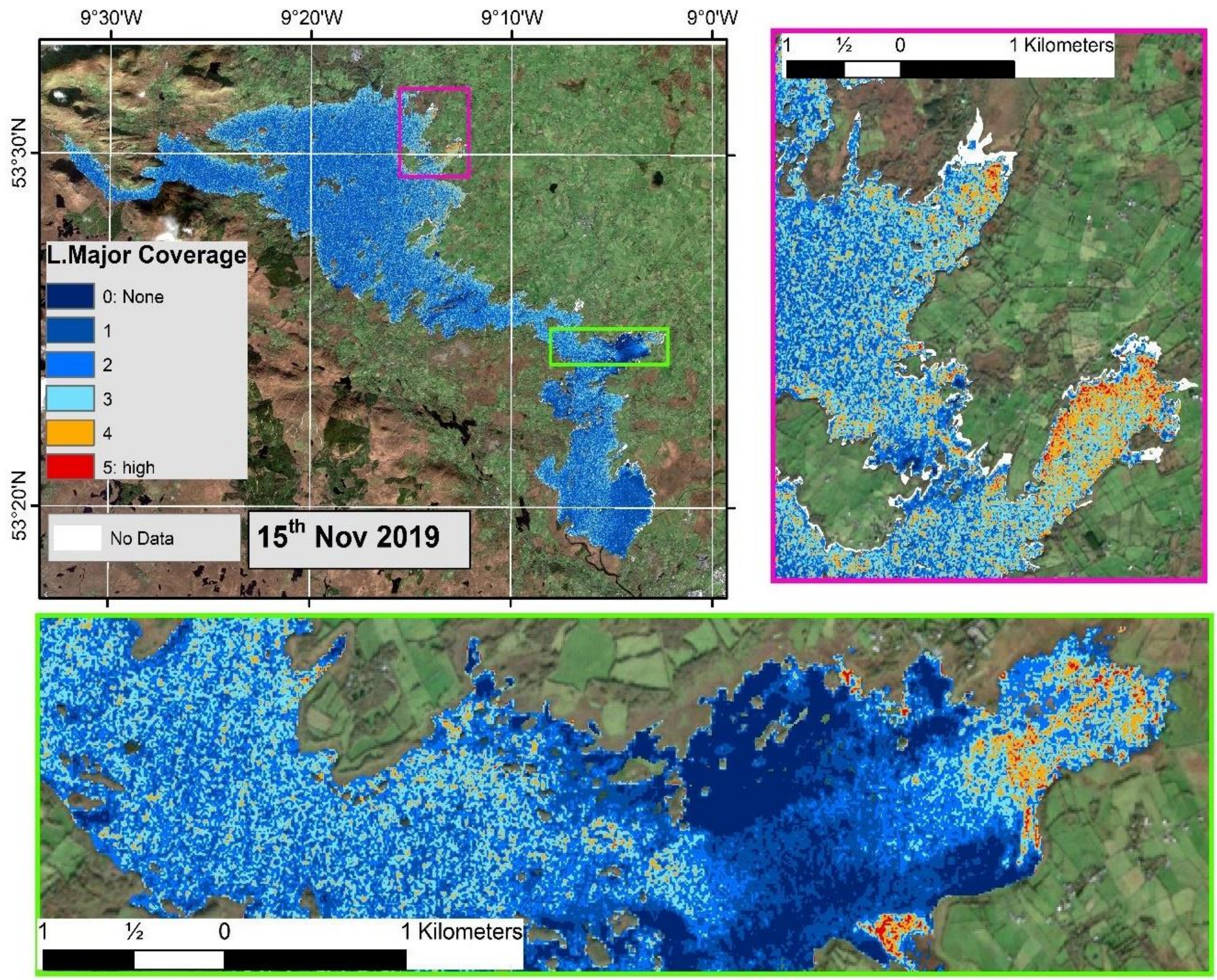


Fig. 2.13. Map of Lough Corrib showing predicted *L. major* coverage derived from Sentinel 2 data for 15th November. Close up views of two locations are shown as pink and green rectangles.

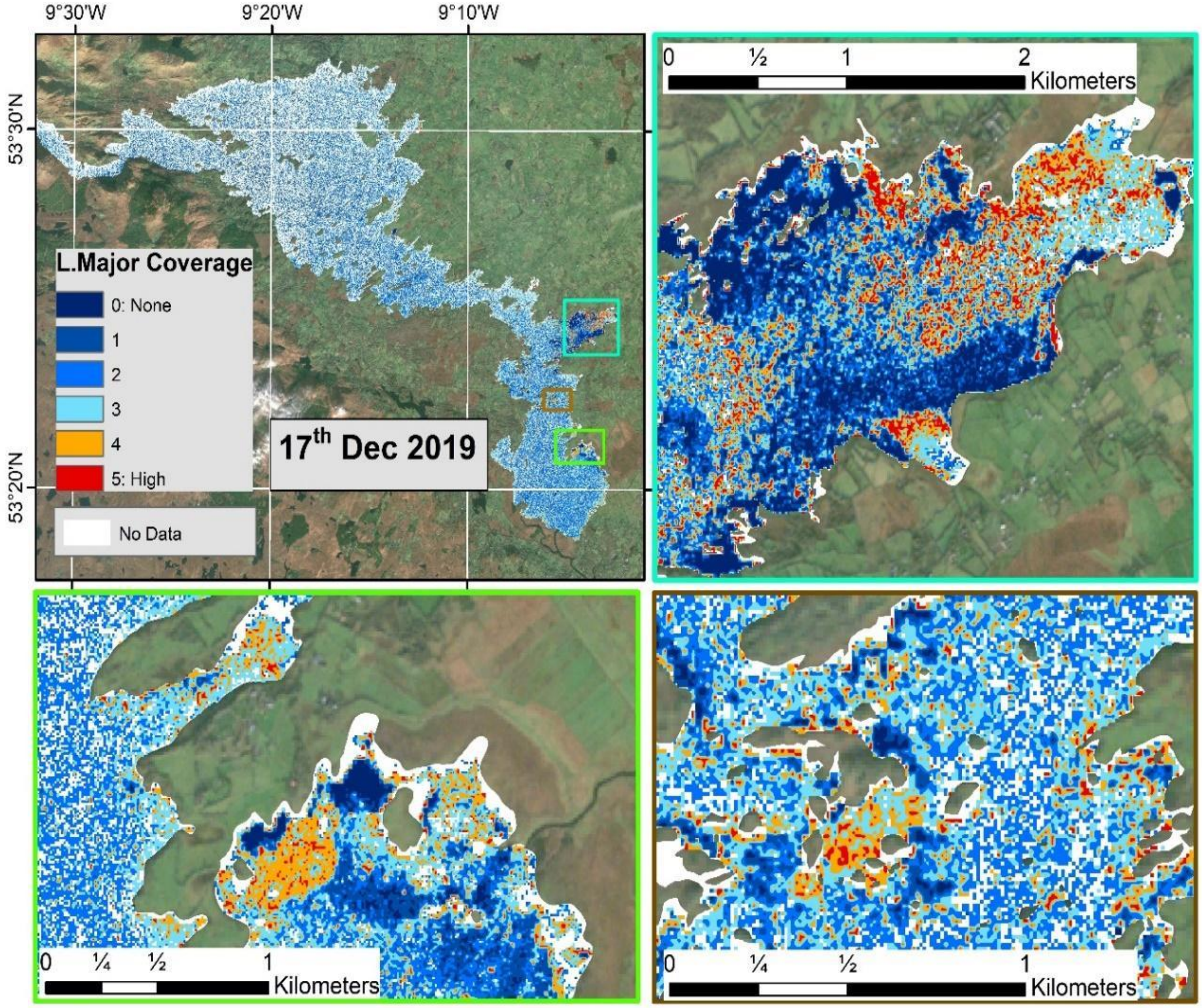


Fig. 2.14. Map of Lough Corrib showing predicted *L. major* coverage derived from Sentinel 2 data for 17th December. Close up views of three locations are shown as green, brown and cyan coloured rectangles.

2.3.5 Comparison of satellite imagery, sonar and ground truth sampling

The data visualisation indicated that sonar derived variables, plant height (bioheight) and distance from the surface, may affect satellite detection of *L. major* (for methods see, Morrissey *et al,.* 2020).

The best fitting model (NDVI~Bioheight + Site + Bioheight X VegDistanceFromSurface) had the lesser Akaike Information Criterion (AIC) of the tested model set; residual plots were homogenous and linear. The effect of bioheight, site, and the interaction between bioheight and the distance of vegetation from the surface on NDVI were significant (GLM P <0.001) (Table 2.4). NDVI was only positively affected by vegetation height where the bottom depth was >2.5 m and vegetation were approaching the surface, meaning that the best satellite predictions referred to tall vegetation in shallow water (Table 2.4 and Fig. 2.15). Scientific sonar data indicated that vegetation was more likely to comprise *L. major* than other macrophyte species in Annaghdown and Carrowgarriff when observed plants are taller than 1.26 m (Fig. 2.16).

Table 2.4 Results for the best-fitting model for NDVI and aquatic vegetation in Lough Corrib.

Variable	Estimate	SE	t-value	$P_r(>\|t\|)$
Intercept	0.074	0.003	22.52	0.001
Bioheight	0.216	0.013	16.08	0.001
Site (Carrowgarriff)	-0.037	0.003	-12.15	0.001
Bioheight X Vegetation Distance from Surface	0.090	0.005	19.32	0.001

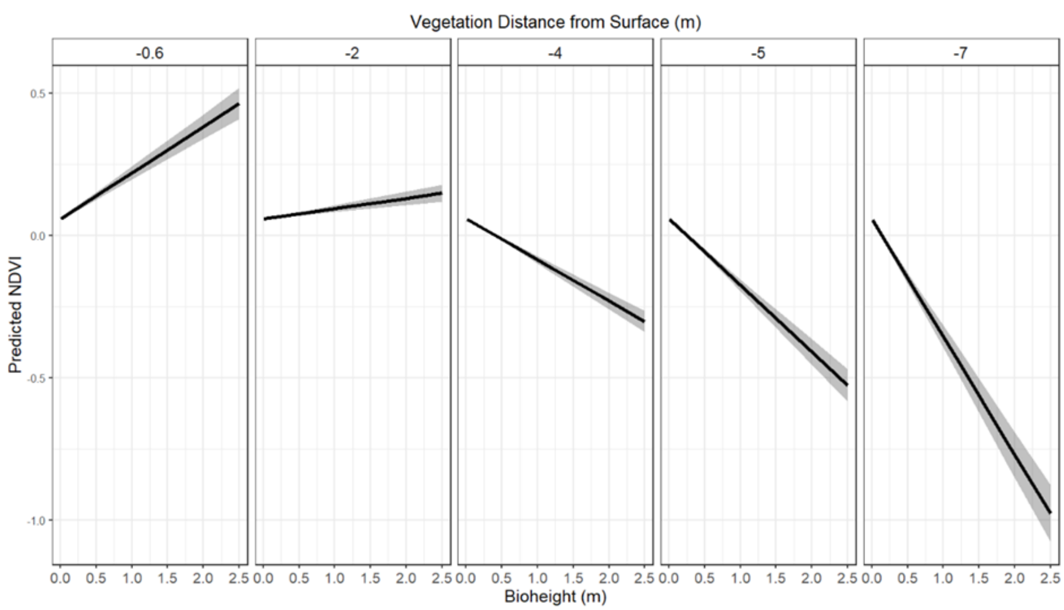


Fig. 2.15 The effect of the distance of vegetation from the water surface and bioheight (the height of the aquatic vegetation) on NDVI values reported by Sentinel-2.

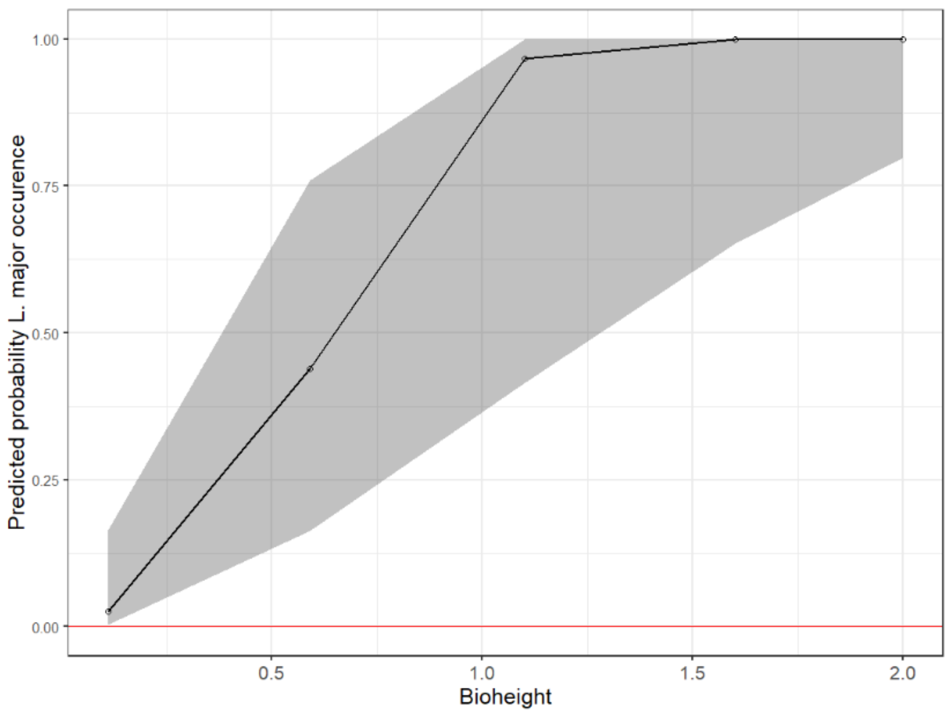


Fig. 2.16 The probability of *L. major* occurrence at a given bioheight reported by scientific sonar across the two sites in Carrowgarriff (SU1) and Annaghdown (SU15) during sampling in 2019.

2.4 Discussion

Overall, this study found that modern sampling techniques should be implemented as they will increase the accuracy and efficiency of *L. major* data collection while also providing much needed quantitative data. Low-cost sonar with simultaneous ground-truth sampling, gathered using Survey123 for ArcGIS, was identified as the most reliable and efficient survey method (for example, SU8 and SU9 took two team members 0.5 day on the water to survey with transects at 40 m spacing. While lower lake survey units, SU17, 19 and 20, took two team members approximately three days to survey with 120 m transect spacing). Low-cost sonar can be successfully applied to the broad range of waters where *L. major* occurs in Lough Corrib with relatively little investment or training. In addition, it can be used to generate important plant and habitat data, such as depth of colonisation, bathymetry, slope and bottom hardness with no additional sampling effort. Low-cost sonar units represent excellent value for money and the largely automated data processing is free of charge once the data owner agrees to "open access" (www.biobasemaps.com). However low-cost sonar was only useful where *L. major* occurred ≥0.4 m below the water's surface, due to propeller depth and associated fragmentation risk and quality control can take a considerable length of time in areas with high vegetation cover.

L. major presence was related to sonar bioheight but this varied across the different survey units sampled. This was probably due to seasonal and location specific factors and highlights the need for simultaneous ground-truth sampling. Indeed, some of the tallest plants recorded were Potamogeton *spp.* in SU20, the lower lake where *L. major* was absent.

Underwater imagery was found to be a highly effective tool for quantitatively sampling aquatic plants and substrate. Results showed that there was typically a 50% chance of a given macrophyte being recorded in a grapnel sample when it had a coverage of 50%. However, macrophyte type had a significant effect on the probability of detection, with charophytes displaying a higher detection than other macrophytes. This result indicates that grapnel sampling is biased towards certain species. Therefore, it is recommended that underwater imagery be used where practical, to provide unbiased and quantitative results. Analysis also revealed that camera model did not affect the results, but practical experience confirmed that different features made macrophyte identification easier and so a high-resolution camera with live-feed and geo-referencing ability is recommended.

UAV's provided high resolution RGB mapping in calm, dry weather and were useful for surveying rocky and shallow areas that are difficult to survey using a boat. The weather requirements for the UAV's trialled made survey planning difficult, but a lot could be achieved in a small timeframe when weather conditions were suitable. For the purposes of mapping *L. major* UAVs were only useful where the weed was at the surface. In this regard, results indicate that seasonal and local growth patterns are important considerations when choosing this survey method. This study also found that UAV surveys were useful for ascertaining the exact location of jute mats in clear shallow waters. Overall, the UAV's used on the project offered a low cost, high-resolution option in comparison to high-resolution (40 cm pixel) satellite imagery (e.g. Worldview 4). However, in contrast to satellite their range was limited. UAV's were also found to be a valuable research tool suitable for the collection of quantitative data on the allofragmentation generated by harvesting and cutting control methods (Meade *et al., submitted for publication*).

The pilot study investigating the utility of Sentinel-2 satellite data for mapping *L. major* at the lake wide scale in Lough Corrib found that *L. major* was related to several multispectral indices, such as NDVI (Karki, 2020). Model results showed the abundance and presence of *L. major* in areas where it had been recorded by the field team, but the model also indicated that it was present in areas where it was not recorded (e.g. Ballindiff Bay). Further training of the model is required to attain a higher level and more accurate predictability by adding field data from the areas where the macrophyte is present and absent before it could be rolled out as a survey tool (Karki, 2020). The value of this approach for distribution mapping of *L. major* at the lake wide scale in Lough Corrib if proved to be successful is that it could be carried out annually at the lake-wide scale without large expenditure using a small amount of ground truthing. However, it requires a large training dataset (polygon format of all macrophyte types in the lake) and it needs a low number of cloud free days which can be relatively rare in the west of Ireland. It also requires expertise in modelling and computer power which is not available in IFI.

The LARC team's comparison of scientific sonar and NDVI calculated from Sentinel-2 satellite data revealed that NDVI was affected by plant height and distance of the plant from the water's surface and found that NDVI was not positively correlated with plant height at depths >2.5 m. This result indicates that if areal field datasets are to be collected for the purpose of improving *L. major* detection by Sentinel-2 satellites then sonar should be used and plant height and distance of the plant from the water's surface should be included as variables.

All methods tested during the project have demonstrated that no one method is suitable for monitoring *L. major* in Lough Corrib. Some methods are more effective in some situations than others; therefore an integrated multi-method approach where tools are selected as appropriate is recommended. Initial focus should be on using sonar with ground-truth samples, as this method has a low technology threshold and is effective across most settings. Where possible ground-truth samples should be obtained using visual observations and underwater imagery as these methods provide robust quantitative results. Managers require accurate, up-to-date data to make information-based decisions. This can be facilitated if data is stored in an integrated sonar and ground-truth GIS dataset with dashboard metrics for each of the survey units identified during the project.

Satellite imagery has the potential to be a powerful, cost-effective and low-carbon tool for mapping *L. major* at the lake-wide scale. However, more field data (e.g. polygon data) is required to improve the algorithm before satellite data can be used as an effective and reliable tool for monitoring and mapping *L. major* in Lough Corrib. Research presented here indicates that additional areal/polygon data should be collected using sonar.

3: Establish the distribution and extent of colonisation of *L. major* in Lough Corrib

3.1 Introduction

Distribution maps are important for displaying the known presence of plant species and can be used to understand habitat preferences and the environmental factors influencing their geographic range (e.g. Spence and Chrystal, 1970). Such data can also play an effective role in the management and control of invasive alien species, identify new areas at risk (e.g. Thapa *et al.,* 2018) and inform appropriate and cost-effective control measures.

Distribution maps can be generated using an array of methods ranging from traditional on-site, observation to modern remote-sensing, for example, satellite and UAV imagery or hydroacoustics (Ghirardi *et al.,* 2019; Millane *et al.,* 2013; Stocks *et al.,* 2019). A number of these methods have been used to document the distribution of *L. major* in Lough Corrib since it was first recorded in the lake in 2005.

In 2020 distribution mapping of *L. major* in Lough Corrib initially focussed on conducting a comprehensive survey of the lower lake to establish if the macrophyte was growing in this ecologically sensitive shallow basin. Subsequently sampling was conducted in the middle lake including the known southern edge of *L. major's* range. Finally, several areas where *L. major* was controlled previously were surveyed. Most of these sites had not been subject to control measures in the previous year.

Historical *L. major* distribution data along with information collected in 2019 (Morrissey *et al*., 2020) and 2020 is combined here to create up-to-date distribution maps of *L. major* in Lough Corrib.

3.2 Materials and methods

3.2.1 Mapping the distribution of *L. major* (2005 to 2020)

L. major distribution data from this study (LARC 2018 to 2020), previous projects, historical surveys and control operations were collated to provide a comprehensive picture of *L. major's* distribution since its discovery in 2005. Arc GIS 10.5 was used to create detailed maps of *L. major* distribution and once validated the data will be moved to Arc GIS online for dissemination purposes.

Lagarosiphon Research Lough Corrib (LARC) 2018-2020

L. major distribution data collected in 2019 was gathered using four methods; quadrat sampling, hydroacoustics with visual and grapnel ground truthing, UAV and control data (Morrissey *et al.,* 2020). Distribution data collected in 2020 was gathered using methods described elsewhere in this report. These include low-cost sonar with visual and grapnel ground truthing (Section 2.2.2), UAV (Section 2.2.3) and control data supplied by the control team. The locations sampled in 2020 are shown in Figures. 3.1 and 3.2.

Post-CAISIE Survey 2013

A lake-wide survey was conducted in September 2013 to collect presence/absence data. Distribution observations were made by snorkelling along pre-determined transects. The survey targeted areas that were considered vulnerable to infestation or had been previously infested (Millane *et al.,* 2013).

CAISIE Project (2009-2012)

Areas shallower than 6m were surveyed comprehensively between 2009 and 2012 using grapnel sampling, bathyscope observations, snorkelling and scuba diving (CAISIE, 2013).

IFI archival data 2005-2007

Extensive sampling of the lake was conducted using snorkelling, grapnels, scuba diving and bathyscope observations. Observations by recreational lake users were also included, following verification by the scientific team (Caffrey and Acevedo, 2007).

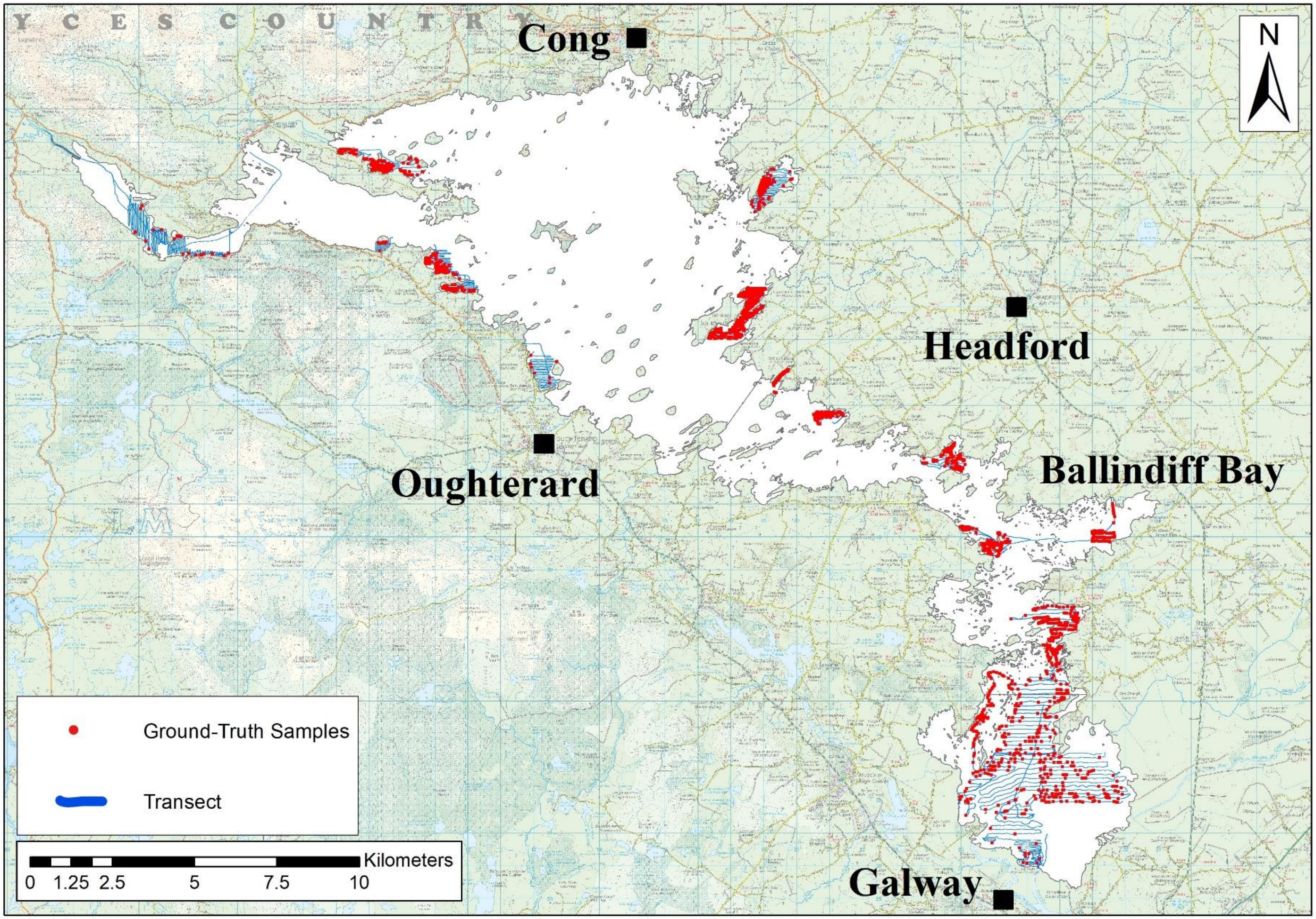


Fig. 3.1. Areas surveyed for *L. major* on Lough Corrib during 2020 using sonar and ground-truth sampling points.

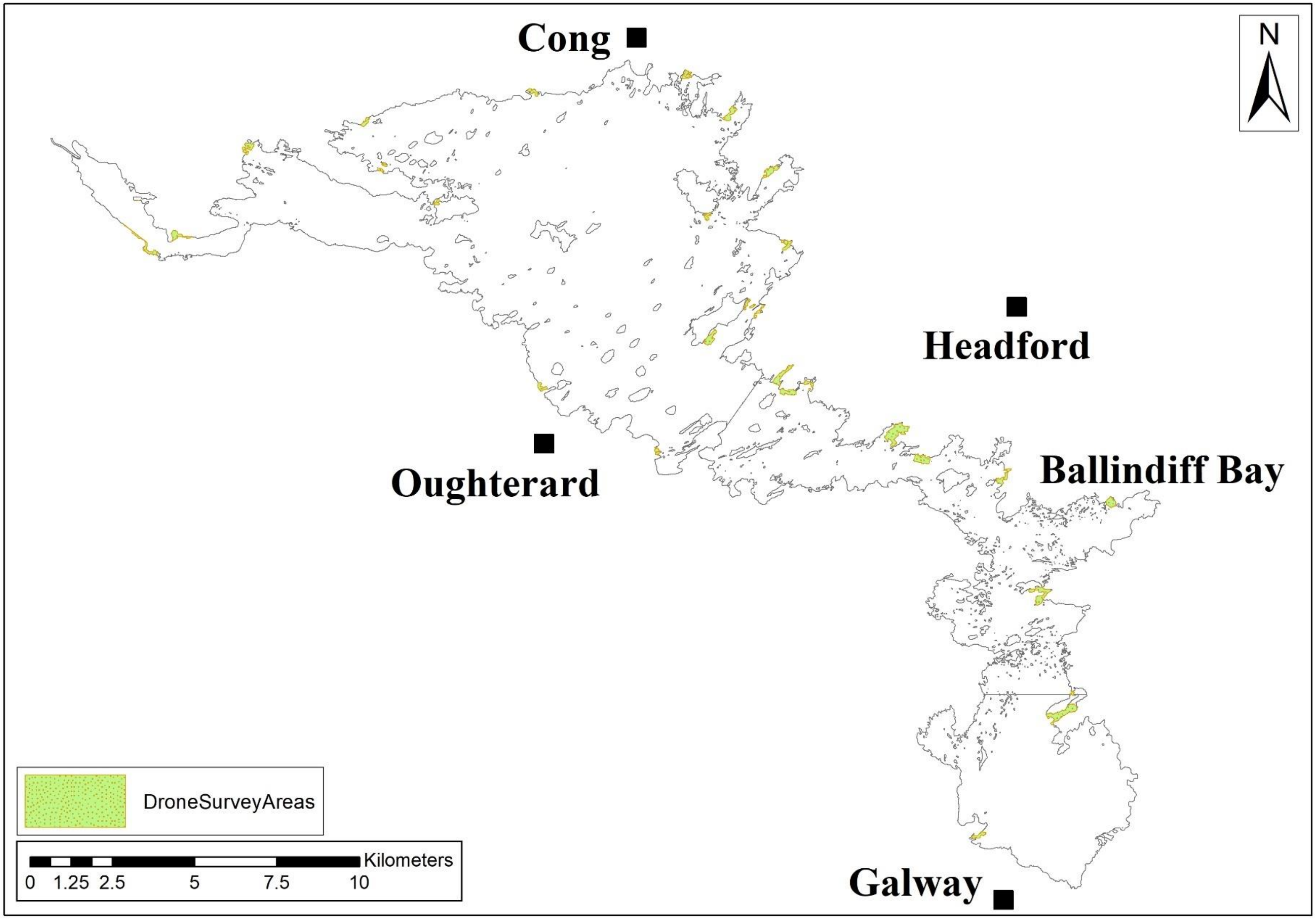


Fig. 3.2. Areas surveyed for *L. major* on Lough Corrib during 2020 using UAV.

3.3 Results

L. major distribution is reported across four different time periods, with a variety of sampling methods and efforts applied.

3.3.1 *L. major* lake-wide distribution (2005 to 2020)

L. major distribution data recorded by the various IFI research projects and the control operations are shown in Figure 3.3. *L. major* has had a wide distribution in the upper lake since 2008. During the following years, *L. major* expanded its range to include areas of the middle lake. To date, there have been no records of *L. major* in the lower lake.

3.3.2 *L. major* distribution in selected survey units, 2018-2020

During 2018-2020 the distribution and area covered by *L. major* was estimated and mapped in detail. Survey units, where updated information on *L. major* distribution was required, were prioritised in 2020 (Figs. 3.4 to 3.13). Ninety-eight relatively small (<50 m^2) isolated patches were recorded as points (Table 3.1). Eight relatively large *L. major* infestations detected by sonar or UAV point covered a total estimated area of 123,025 m^2 (Table 3.1) and occurred in five survey units: SU1_Maam River and Ballynalty (four areas >50m^2); SU2 (Inishlannaun – Bob's island); SU3 (Doorus); SU8 (Ballynalty) and SU 15 (Annaghdown).

Table 3.1 The estimated area (m^2) of large infestations of *L. major* in Lough Corrib 2018-2020. The number of small infestations is also highlighted. Area of infestation in hectares (ha) is also shown.

Survey unit	Total Area of infestations (m^2)	Number of additional point records
SU1	56,748 (5.6747 ha) x 4 areas: (Drumsnauv Bay-35,815.64 m^2; Raughillaun 17,537.14 m^2 and 388.96 m^2; Carrowgariff-3,005.95 m^2)	4
SU2	1,079 (0.1079 ha) x 1 area	0
SU3	5,925 (0.5925 Ha) x1 area	10
SU6	-	14
SU7	-	2
SU8	13,958 (1.3958 ha) x 1 area	10
SU10	-	41
SU12	-	2
SU13	-	8
SU15	45,315 (4.5315 ha) x 1 area	7
Total	**123,025 (12.3025 ha)**	**98**

The largest infestations were in SU1 (Maam River and Drumsnauv) followed by SU15 (Annaghdown) (Table 3.1). The largest infestation in SU1 was present in Drumsnauv Bay. This area was subject to a weed harvester trial in 2019 and has been a problem area for the control team for many years due to the rocky and silty substrate which makes it unsuitable and difficult for existing control measures in use on the lake (Morrissey *et al*., 2020). The three additional infestations (>50m^2) in SU1 measured 388.96m^2, 3,005.95m^2 (near Carrowgariff), 17,537.14m^2 (Figs. 3.4 and 3.5).

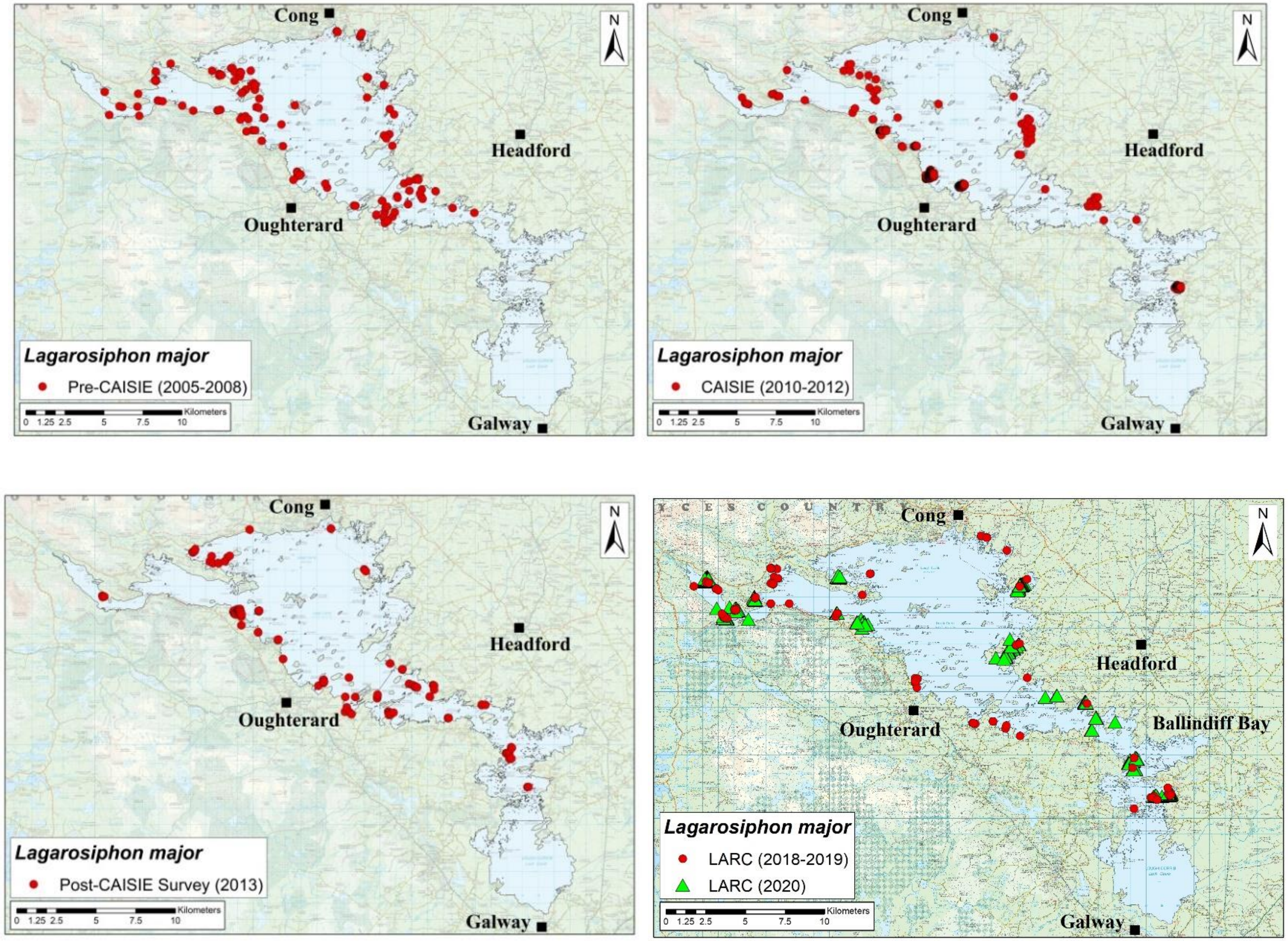


Fig. 3.3. Distribution of *L. major* in Lough Corrib, 2005-2020.

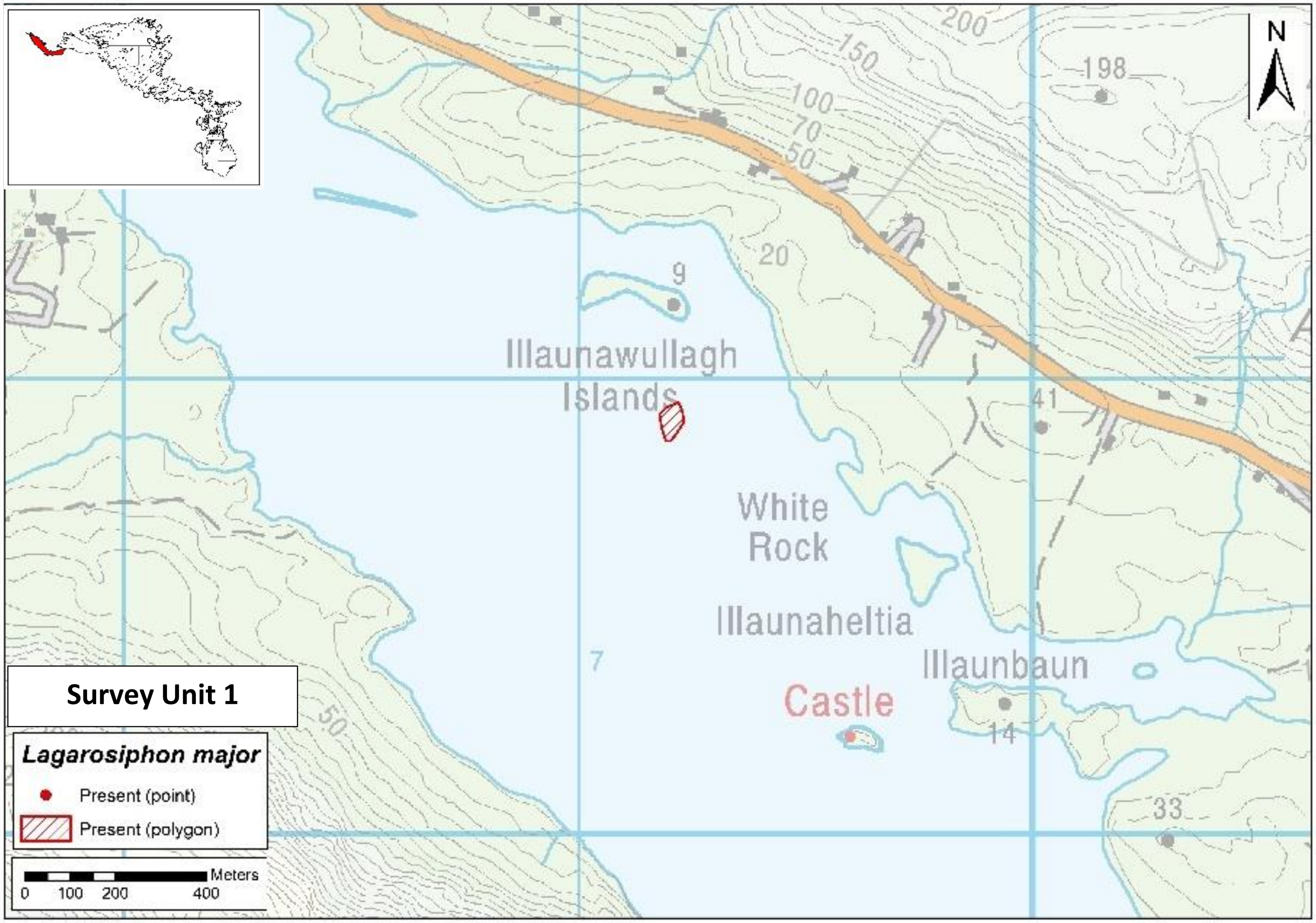


Fig. 3.4. *L. major* distribution in survey unit 1 (Maam/Drumsnauv Bay)

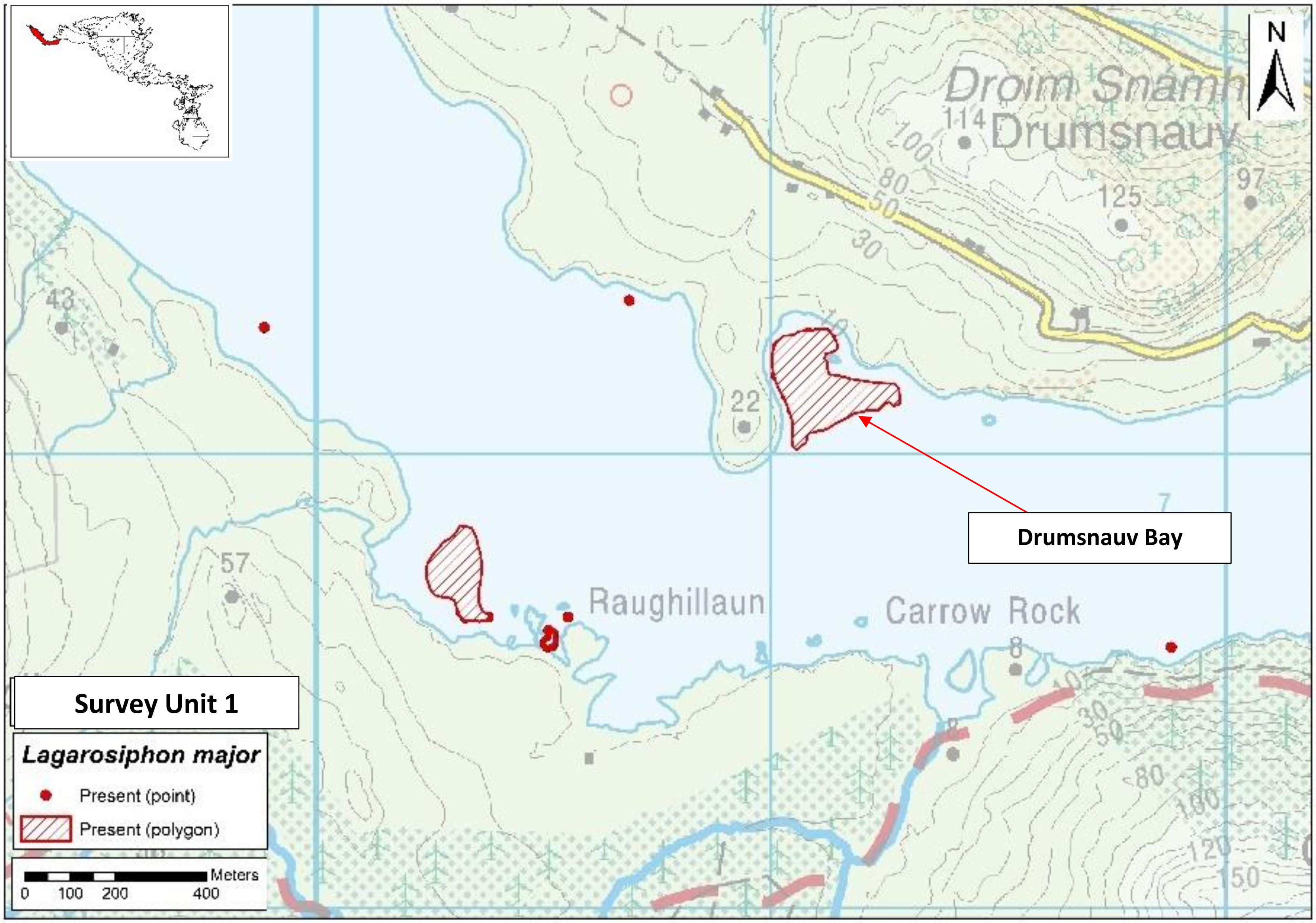


Fig. 3.5. ***L. major*** **distribution in survey units 1 (Maam/Drumsnauv).**

Fig. 3.6. ***L. major*** **distribution in survey unit 2 (Inishlannaun - Bob's Island).**

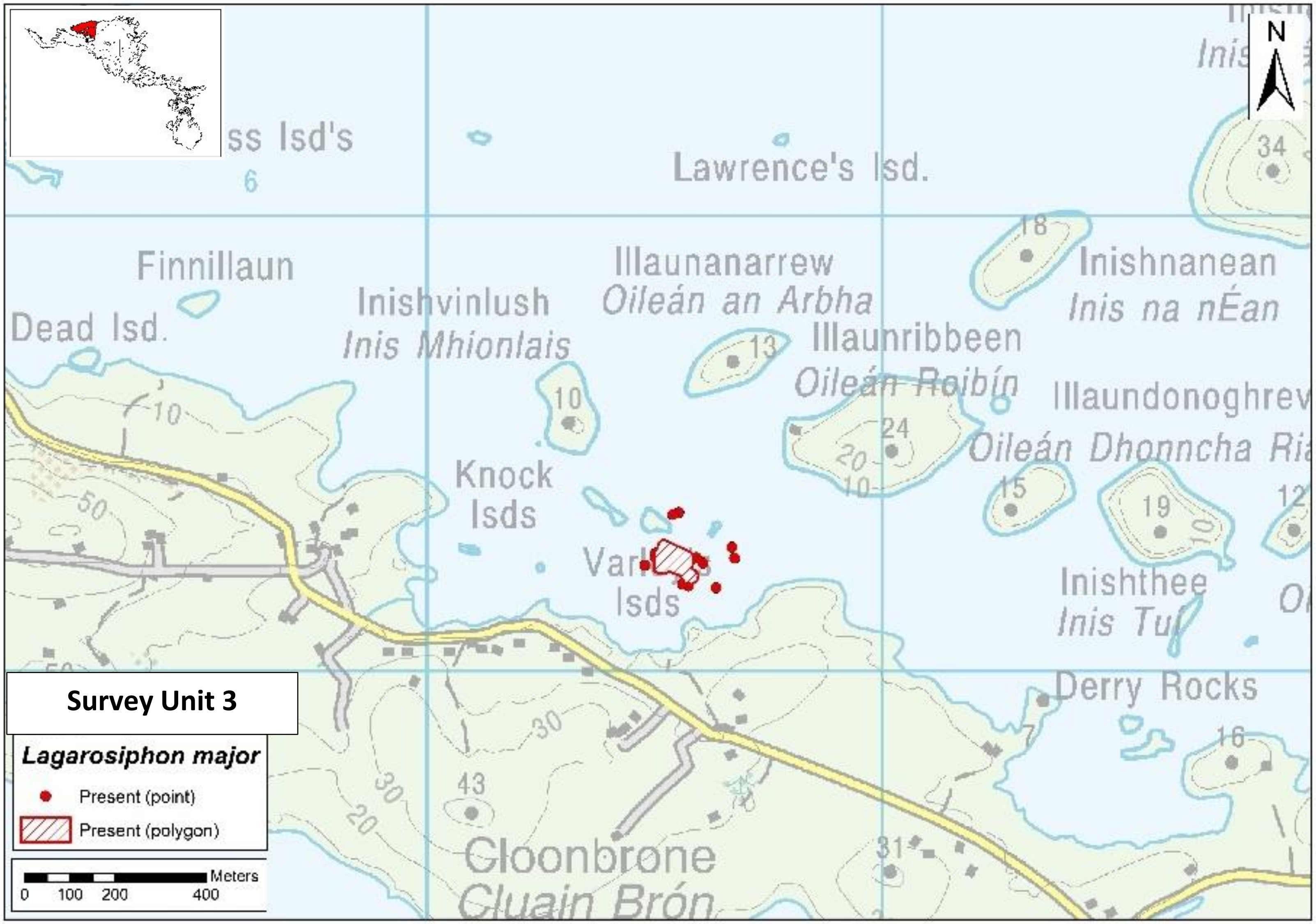


Fig. 3.7. ***L. major*** **distribution in survey unit 3 (Doorus/Cornamona River).**

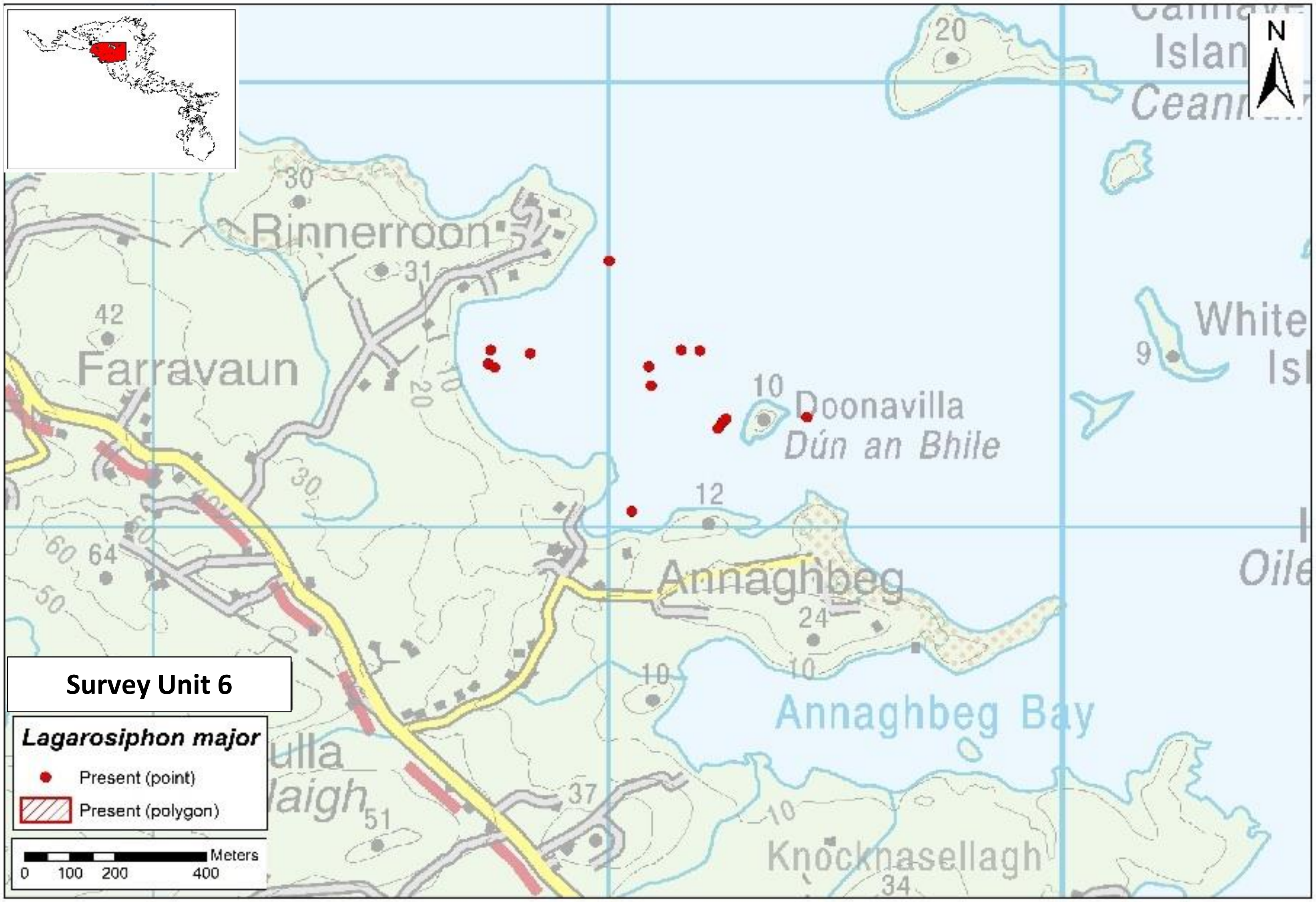


Fig. 3.8. ***L. major*** **distribution in survey unit 6 (Rinnerroon Bay).**

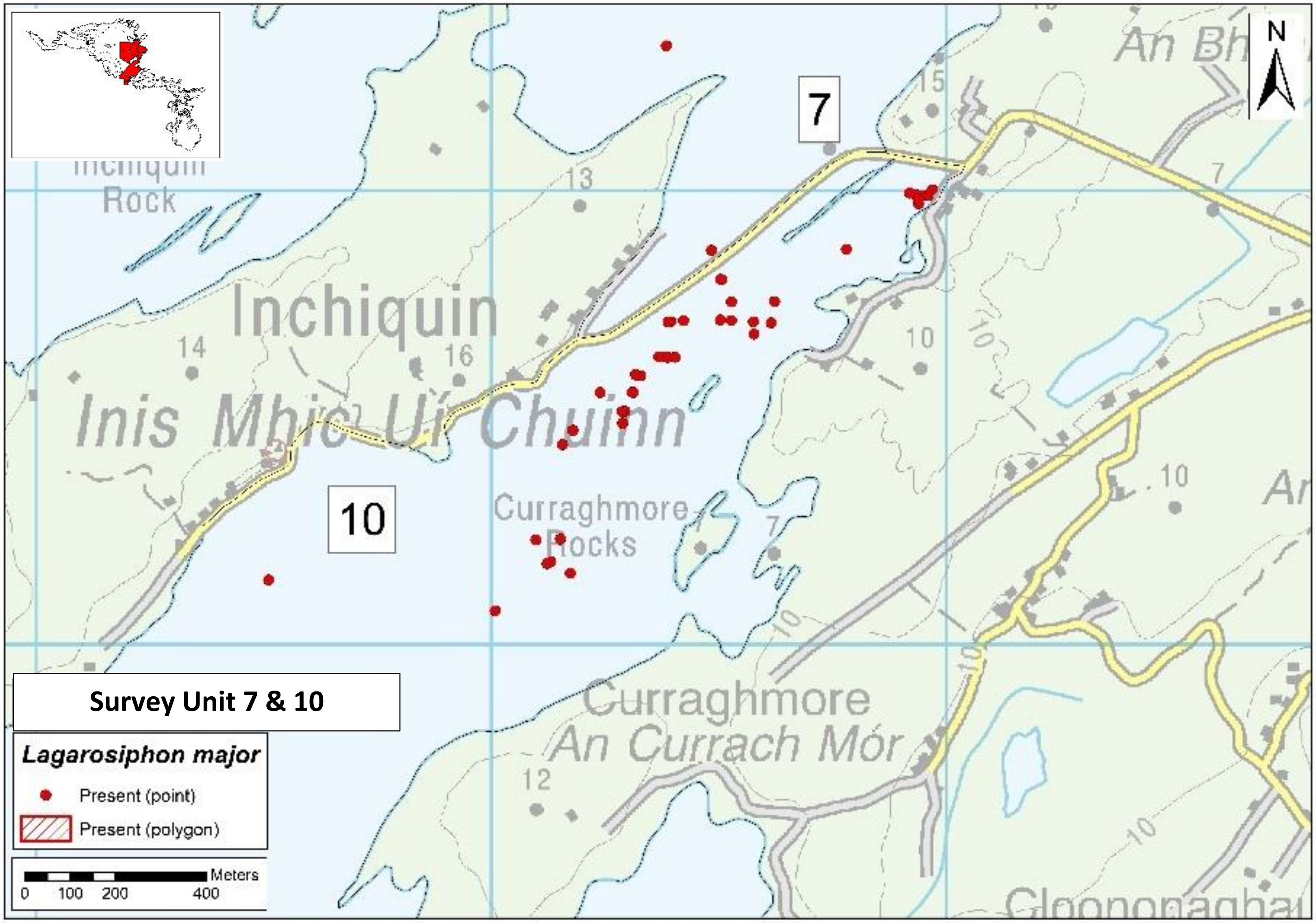


Fig. 3.9. ***L. major*** **distribution in survey units 7 (Ballycurrin) and 10 (Oughterard/Greenfields).**

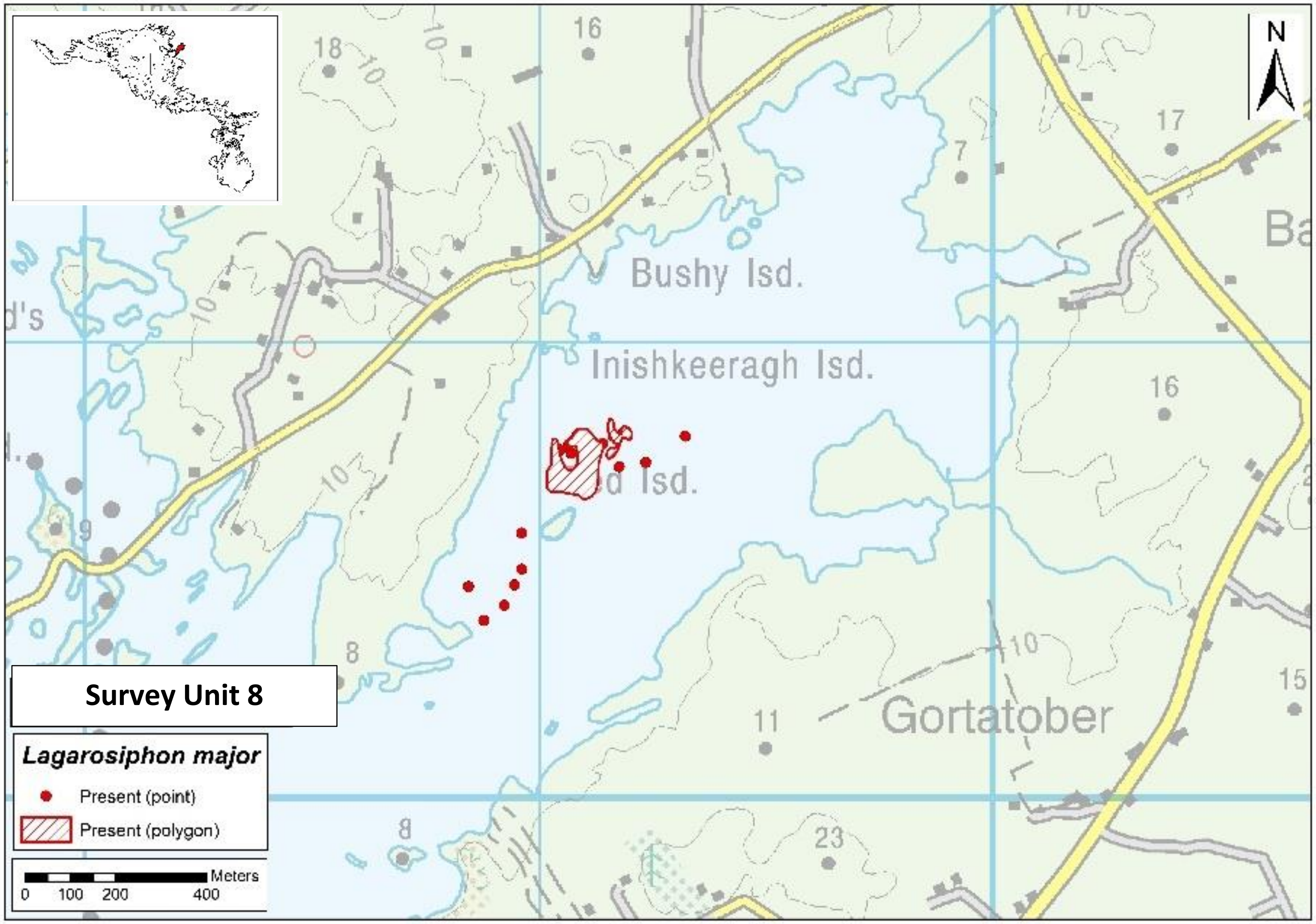


Fig. 3.10. ***L. major*** **distribution in survey unit 8 (Balynalty).**

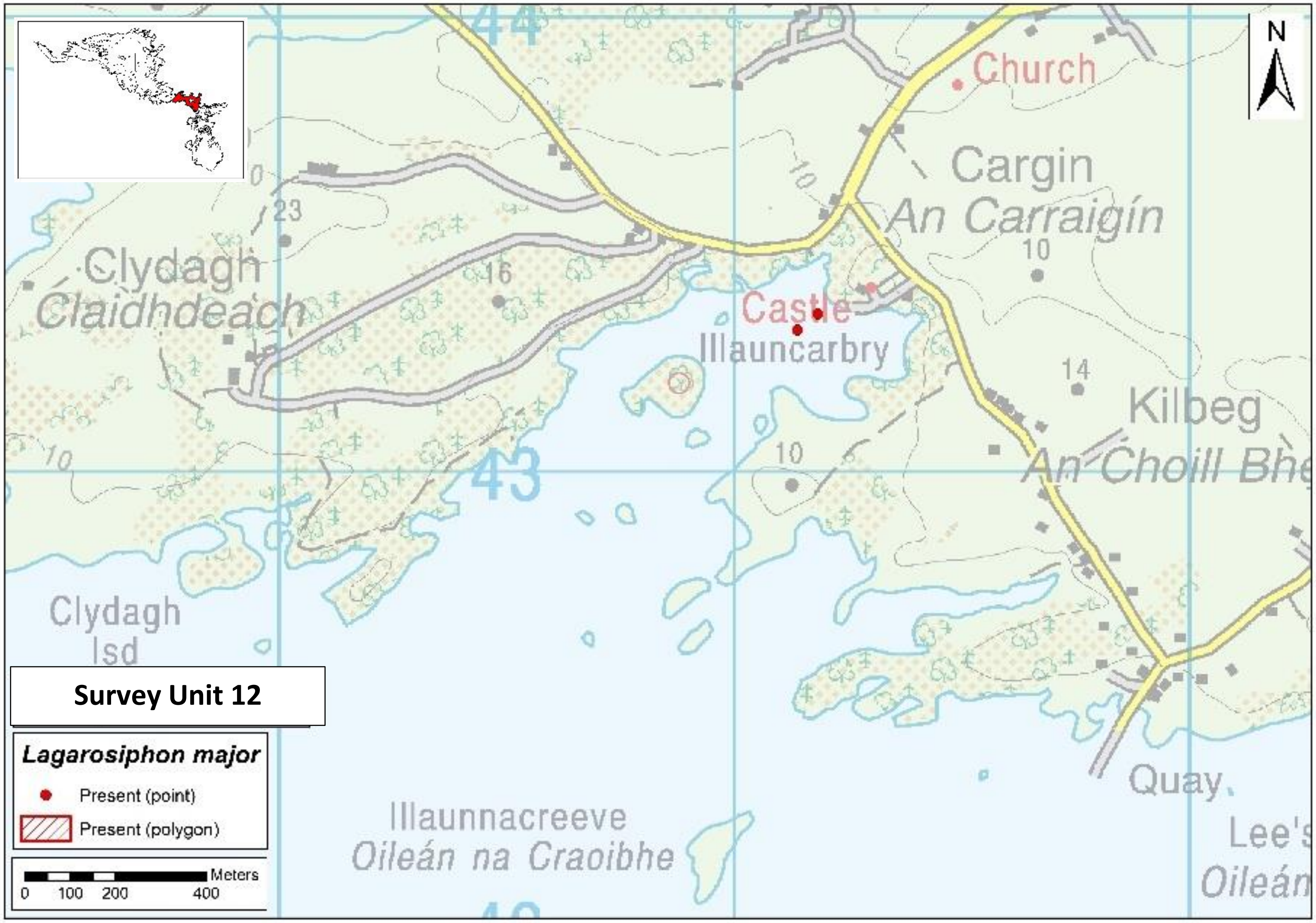


Fig. 3.11. ***L. major*** **distribution in survey unit 12 (Clydagh).**

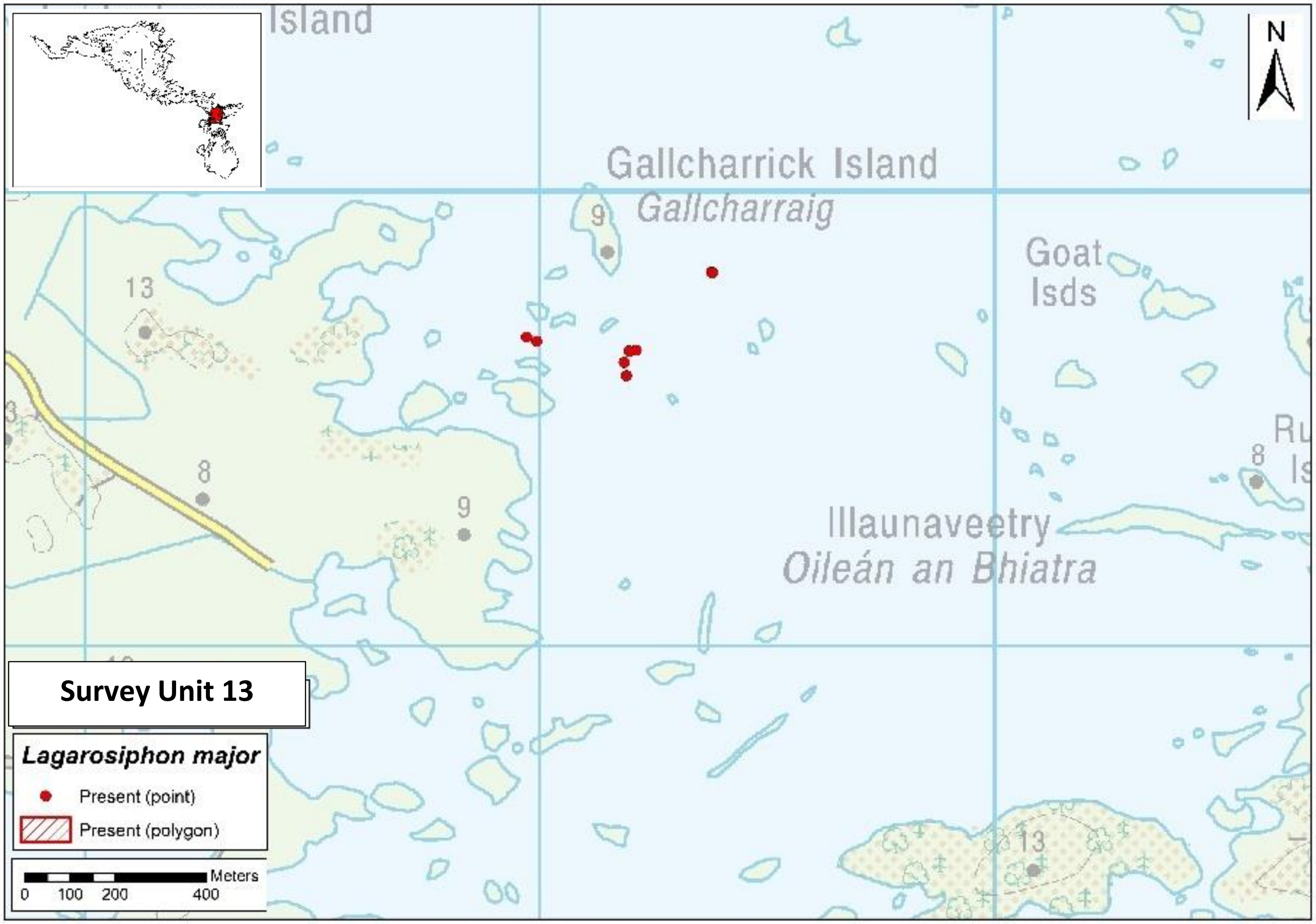


Fig. 3.12. ***L. major*** **distribution in survey units 13 (Opposite Ballindiff Bay, near Saddle Island).**

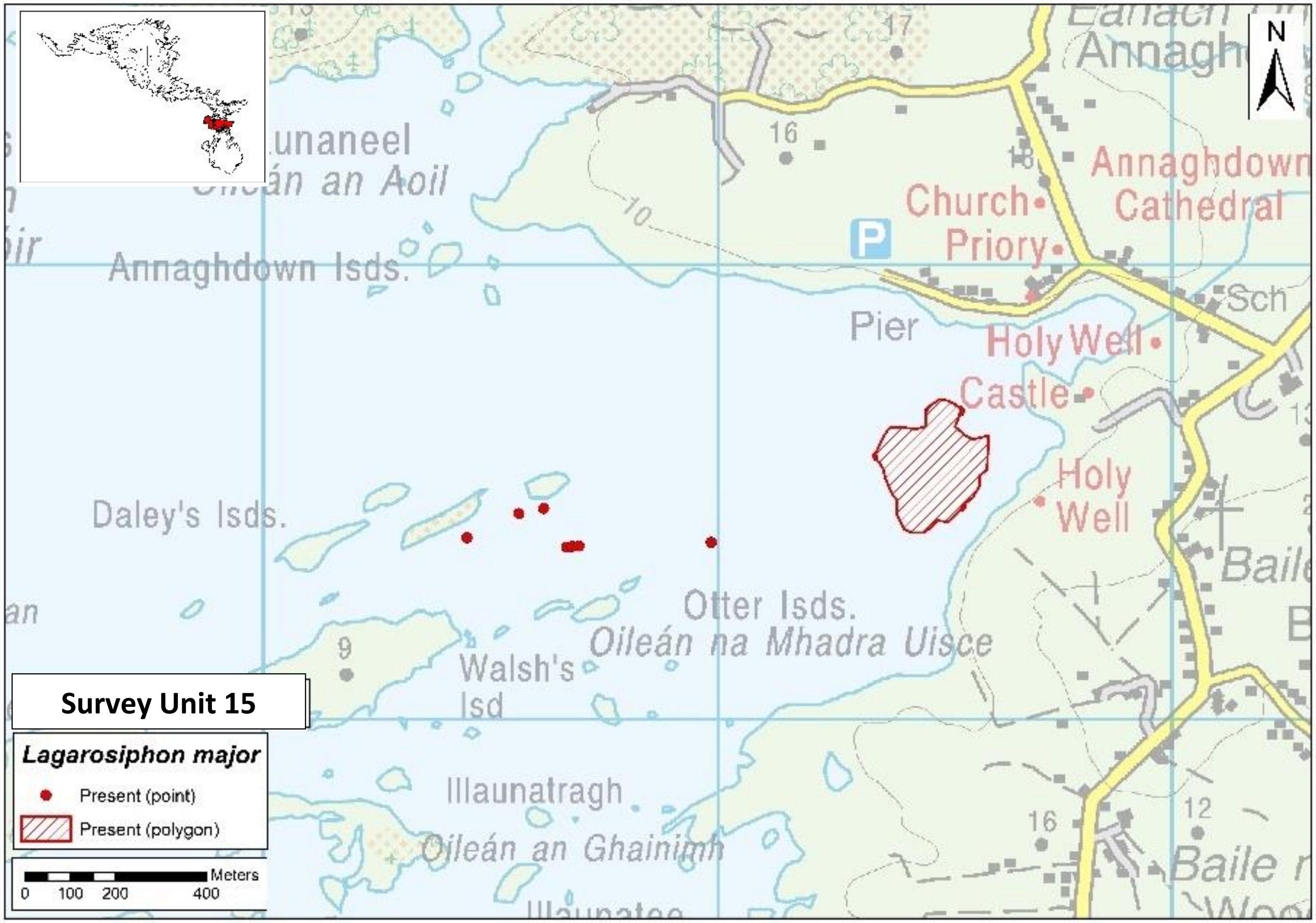


Fig. 3.13. ***L. major*** **distribution in survey unit 15 (Annaghdown).**

3.4 Discussion

Prior to the initiation of a control programme for *L. major* in Lough Corrib in 2008 there was an estimated 92 ha (110 sites) present in Lough Corrib (Caffrey *et al*., 2011). Between 2008 and 2013 an additional 19.67 ha of lake was infested by *L. major* (Millane, 2013). During that period coordinated control measures, including mechanical cutting and harvesting, jute matting and manual removal (hand picking) resulted in the eradication of the invasive macrophyte from 94.86 ha of the lake (86.38% treated) (Millane, 2013) (Table 3.2). In late 2013 it was estimated that 31.31 ha of *L. major* persisted in the lake and required treatment. The *L. major* control programme has continued on Lough Corrib since 2013 and an estimated 12 ha has been treated annually. In 2020 eight relatively large infestations (>50m^2) of *L. major* were identified in Lough Corrib covering a total estimated area of 123,025m^2 (12.3ha). An additional ninety-eight relatively small (<50 m^2) isolated patches were also recorded. In total *L. major* was recorded in 10 survey units, SU1, SU2, SU3, SU6, SU7, SU8, SU10, SU12, SU13, SU15. The eight larger infestations were recorded in five survey units: SU1_Maam River and Drumsnauv (4 areas >50m^2); SU2 (Inishlannaun – Bob's island); SU3 (Doorus); SU8 (Ballynalty) and SU 15 (Annaghdown) (Table 3.1). The largest single area of infestation recorded during 2020 was in SU15 (Annaghdown – 45,315 m^2), while SU1 (Maam River and Drumsnauv) had the largest infestation (56,748 m^2) of *L. major* occurring in 4 areas and at least four additional sites.

Lake-wide distribution maps from four different sampling phases show that *L. major* progressed through a rapid range expansion when it was first introduced into Lough Corrib. Comparison with the 2013 distribution shows that the area of infestation has decreased, but the distribution of *L. major* has widened across the lake since that time. Initially, it was mainly distributed throughout the western arm, upper lake and northern section of the middle lake. Since 2010-2012, it has continued to spread slowly towards the lower lake. Extensive sampling carried out in 2019 and 2020 revealed that there are still no records of *L. major* in the lower part of Lower Lough Corrib; however, the southern edge of its distribution in SU15 (Annaghdown) is approaching this boundary. Therefore this area should be one of the areas prioritised for control measures and improved containment efforts.

4: Determine the influence of habitat and environmental factors on *L. major*

4.1 Introduction

Lough Corrib is a large lake that varies greatly spatially in terms of habitat and environmental variables from north to south and east to west (Krause and King, 1994). *Lagarosiphon major* has successfully invaded sites in the western arm, as well as the upper and middle lake (Millane *et al,.* 2013; Morrissey *et al.,* 2020) (Millane *et al.,* 2013). This invasive plant exhibits a wide range of variability at individual sites in its capacity to successfully establish itself and develop large monocultures. *L. major* also displays a varied response to control efforts throughout the lake, with some sites requiring annual control efforts, while others do not. Further to this, apparent declines, unrelated to control operations, have recently been reported (Oirbsean, pers. comm.). The mechanisms underpinning this variability are not understood but it is likely that habitat and environmental factors play an important role (Pulzatto *et al.,* 2019). Filling this knowledge gap may identify more effective control strategies and improve predictions of *L. major* distribution under current and changing conditions, e.g., climate and eutrophication.

The invasive ability of a species is an interaction between the invasive species and the biotic (e.g. competitors) and abiotic characteristics of the invaded ecosystem (Funk, 2013). Abiotic factors such as light, temperature, depth, pH, alkalinity, nutrients and substrate all interact with essential biological processes such as photosynthesis and respiration (Bornette and Puijalon, 2011; Wiik *et al.,* 2013). These processes govern the outcomes of competitive interactions. This makes the task of determining the influence of habitat and environmental factors on plant community structure difficult. Aquatic plant invasion is typically mediated by abiotic variables at broad spatial scales and biotic variables at fine spatial scales (Pulzatto *et al.,* 2019). Light, temperature, depth, sediment type, and the availability of nutrients and carbon are major abiotic factors affecting aquatic plant growth (Cavalli *et al.,* 2012; June-Wells *et al.,* 2016; Martin and Coetzee, 2014). Previous research on Lough Corrib has shown that these abiotic factors vary substantially throughout the lake (Morrissey *et al.,* 2020).

Photosynthesis and growth are typically stimulated by seasonal increases in temperature and light. In this regard, the growth pattern of *L. major* in Lough Corrib represents a significant unexplained anomaly. Temperatures between 18 and 23°C are considered optimal for *L. major* growth although it can sustain growth at temperatures as low as 2.6 °C (Lambertini *et al.,* 2012; Mckee *et al.,* 2002). In Lough Corrib *L. major* growth peaks during winter (Caffrey *et al.,* 2011) when temperatures are typically below 10°C (Morrissey *et al.,* 2020). This winter growth is likely accommodated by *L. major's* phenotypic plasticity in relation to temperature and light (Riis *et al.,* 2010). Indeed, studies have shown that it can maintain growth under varying light conditions (Hussner *et al.,* 2011, 2015). However, decreases in water clarity have coincided with *L. major* declines in New Zealand (Coffey and Clayton, 1988; Wells and Clayton, 1991).

Photosynthesis and growth in submerged aquatic plants is often limited by the availability of free CO_2, nitrogen and phosphorous. These key elements were found to be important in controlling *L. major* size in New Zealand's freshwaters (Riis *et al.,* 2010). Free CO_2 availability is directly related to pH, alkalinity and temperature and varies on a seasonal, diurnal and episodic basis in lakes (Christensen *et al.,* 2013; Sand-Jensen *et al.,* 2019). In winter, free CO_2 concentrations are high and excess CO_2 is emitted to the atmosphere. During the summer CO_2 concentrations are low due to depletion by photosynthetic organisms (Müller *et al.,* 2016). Alkalinity, pH and temperature vary across Lough Corrib (Morrissey *et al.,* 2020), consequently associated variations in free CO_2 are expected.

In acidic waters the main carbon source for plant growth is free CO_2 while bicarbonate (HCO_3^-) is the most abundant form in calcareous waters (pH 6.3-10.1) (Bain and Proctor, 1980; Yin *et al.,* 2017). HCO_3^- is a more costly carbon source (Hussner *et al.,* 2016) but many plants that occur in Lough Corrib, such as *L. major* and charophytes are capable of bicarbonate use (Yin *et al.,* 2017). Indeed, charophytes are highly efficient bicarbonate users. Differences in bicarbonate uptake can provide a significant advantage when CO_2 becomes limited in the environment. Differences in bicarbonate use efficiency across alkalinities has been identified in *L. major* and this may influence its distribution via species interactions (Cavalli *et al.,* 2012; Yin *et al.,* 2017). Research has found that *L. major's* high plasticity under low CO_2 and high pH conditions enabled it to outcompete *Ceratophyllum demersum* (Stiers *et al.,* 2011).

During photosynthesis, stands of submerged aquatic plants raise pH and oxygen (O_2) concentrations and deplete free CO_2 concentrations in their immediate environment (James *et al*., 1999). Photosynthesis is constrained by high pH values (>9.5) and the limit for bicarbonate uptake is at pH 10.4 (Christensen *et al.* 2013; Stiers *et al.* 2011). Charophytes are adapted to low nutrient conditions, high pH and high alkalinity. It has been suggested that charophytes ability to buffer environmental pH increases via calcification alongside their more efficient HCO_3^- use at high pH and lower respiration rates appear to account for their ability to dominate in oligotrophic hard waters (Sand-Jensen *et al.* 2018). There is also evidence that *Chara* spp. can outcompete tall canopy forming *Potamogeton pectinatus* (Fennel pondweed) by reducing HCO_3^- levels and acting as a nutrient sink (Hidding *et al.* 2010). In clean marl lakes, such as lower Lough Corrib, intense photosynthesis of *Chara* spp. during the summer can cause phosphorous to be immobilised as it co-precipitates with calcite (Wiik *et al.* 2013).

Sediment characteristics affect submersed aquatic plant species distributions (Barko and Smart, 1986). Phosphorous and nitrogen are important for plant growth and delays in *L. major* growth have been documented in oligotrophic lakes compared to eutrophic lakes (Rattray *et al.,* 1994). Studies also indicate that *L. major* displays a preference for sheltered sites with fine sediment (Howard-Williams and Davies, 1988). Furthermore, *L. major* biomass and the sedimentary organic matter are significantly positively correlated (Bertrin *et al.,* 2017). Macronutrients bioavailability varies with time and can be influenced by biologically mediated chemical reactions, such as calcification, a process commonly mediated by charophytes (Wiik *et al.,* 2013). Rooted plants that form surface canopies, such as *L. major* can use nutrients and gases from the water column, sediment and air (Barko and Smart, 1986). This flexibility likely contributes to its success across a wide range of habitats in Lough Corrib.

This study aimed to investigate further the knowledge gap in relation to the effects of habitat and environmental variables on *L. major* in Lough Corrib.

4.2 Materials & methods

4.2.1 *L. major* percentage cover dataset 2019-2020

L. major percentage cover (0-100%) was gathered during 2019 and 2020 using a range of sampling techniques (random survey quadrats, sonar, UAV, visual observations and control team estimates) described in Sections 2.2 & 3.2 and Morrissey *et al.* (2020).

4.2.2 Habitat variables

Fetch

Fetch length (m) (distance wind can blow in a specific direction over unobstructed open water) was calculated for all sampling sites in the *L. major* dataset, using the R package "Waver" (Marchand and Gill, 2017). Fetch length was calculated for the main bearings (0°, 45°, 90°, 135°, 180°, 225°, 270°, 315°). A spread of 22.5° was added to the main bearing to produce weighted average fetch lengths that were proportional to the spread. This measure is averaged across bearings to provide a reasonable measure of the overall wind exposure at a specific aquatic location.

Depth, bottom hardness, distance from shore, slope and aspect

Depth (bathymetry) and bottom hardness were estimated from sonar collected during the project (see section 2.2.2). Bottom hardness (dB) was grouped into three categories; 0 – 0.25 (soft), 0.25 – 0.4 (medium) to 0.4 – 0.5 (hard) (Navico, 2019). A polygon of the lake was used to calculate the distance of each point from the shore and lake bathymetry was then used to calculate slope and aspect values. All data were exported for each location in the *L. major* dataset using ArcMap 10.5

4.2.3 Environmental variables

Temperature and light intensity

Temperature and temperature/light data loggers were deployed at multiple mooring sites across the lake in 2019 and 2020 (Fig. 4.1). Benthic temperature data loggers (n=38) recorded temperature (ºC) data every six hours from December 2018 to June 2019 (Morrissey *et al.,* 2020). Temperature/light data loggers (n=31) were subsequently deployed on a sub-set of the moorings at one metre below the surface (2) and were programmed to record data every 20 minutes, from July to October 2019. In 2020, temperature data loggers (n=30) and temperature-light data loggers (n=37) were deployed on moorings at one metre below the surface logging every 15 mins from March to October. Monthly mean values for light (lux) and temperature (°C) were calculated for each logger and spatially interpolated in ArcGIS (Fig. 4.3).

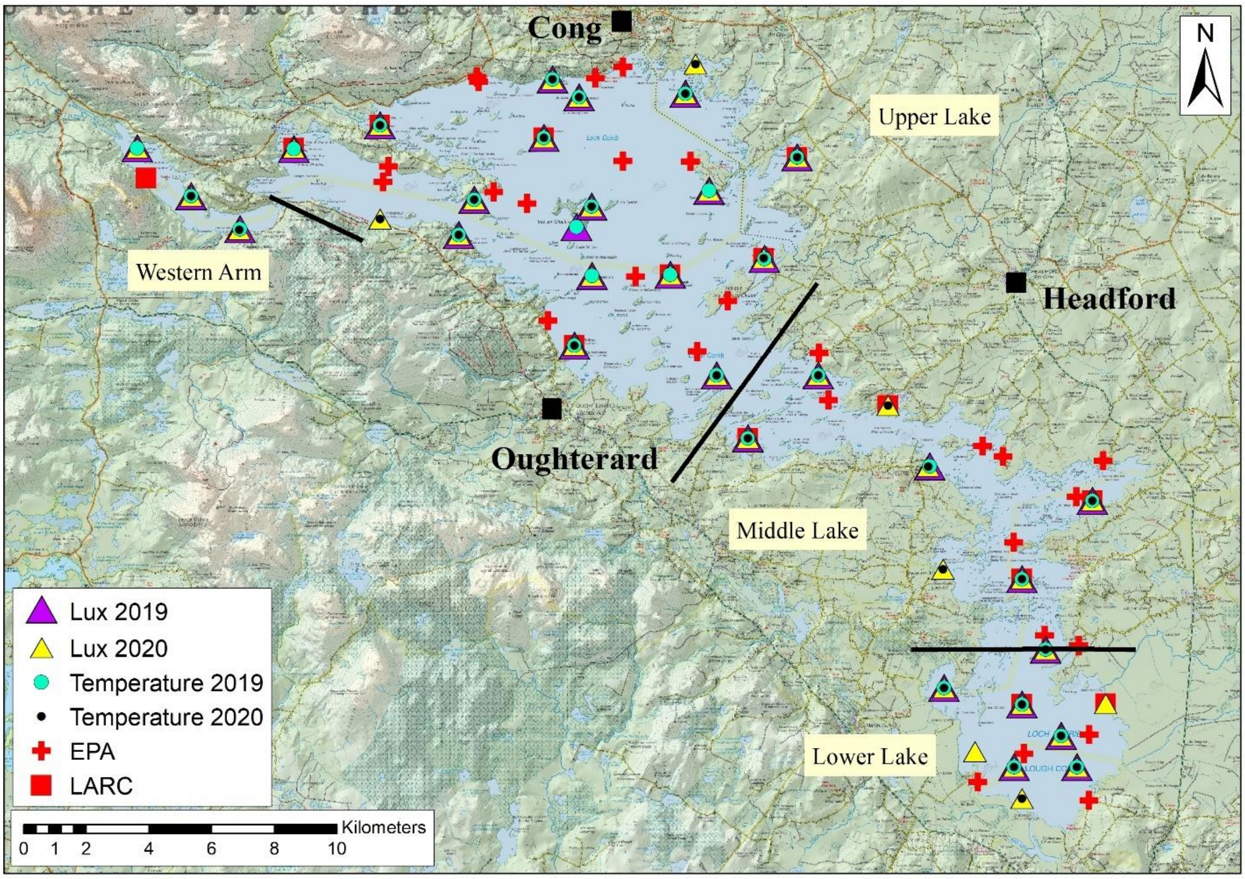


Fig. 4.1. Location of temperature and temperature-light data logger sites on Lough Corrib 2019 and 2020. Locations of EPA and IFI sites where total alkalinity (as $CaCO_3$) and pH were monitored in 2019 and 2020 are also indicated.

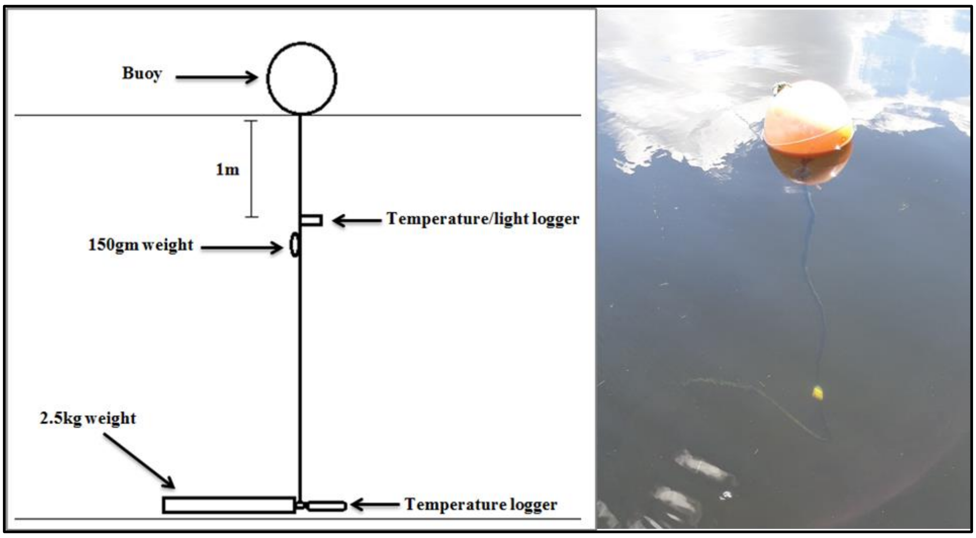


Fig. 4.2. Graphic and photograph of the lake-wide logger mooring deployment.

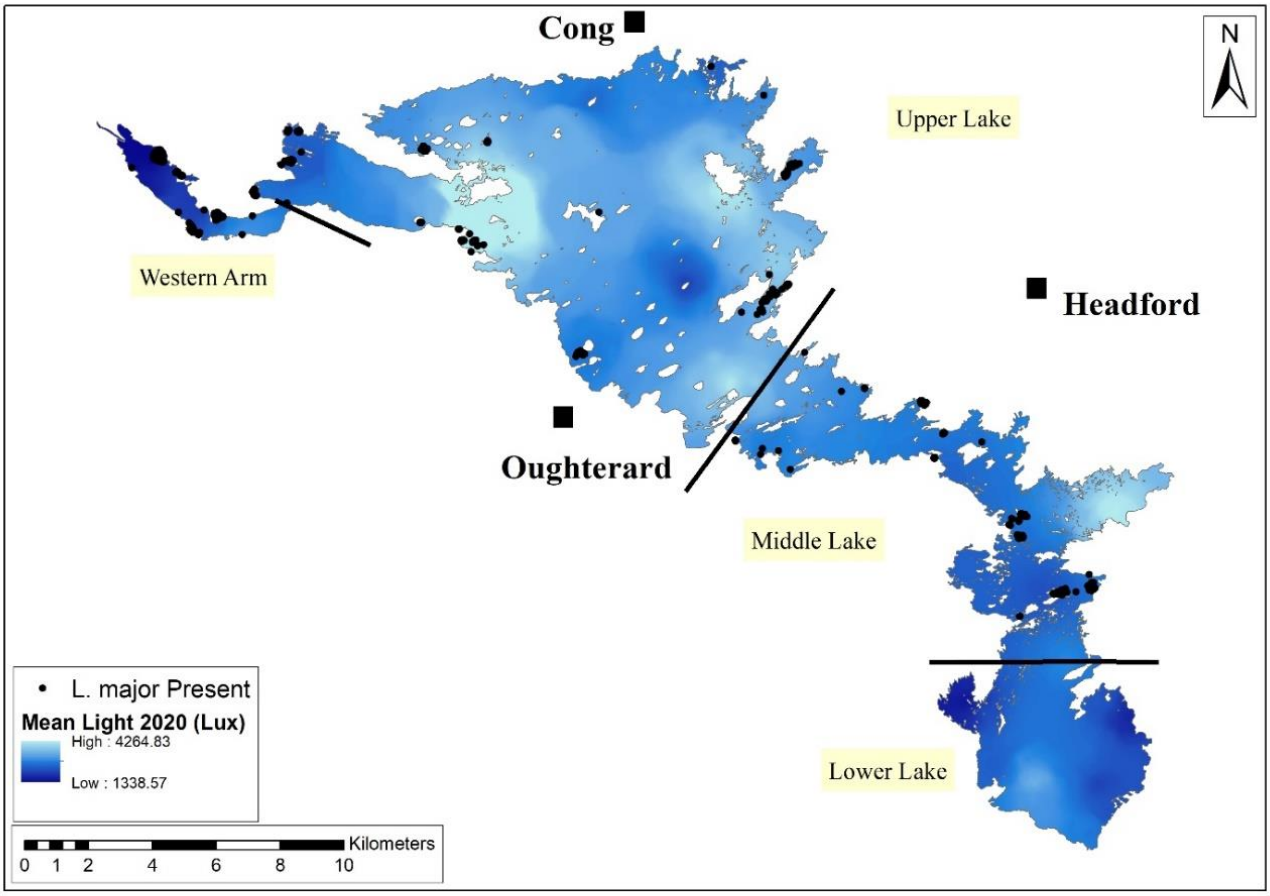


Fig. 4.3. Interpolation of mean light (Lux) in Lough Corrib, March to October 2020 with *L. major* presence 2019-2020 displayed for reference.

Alkalinity and pH

Mean monthly total alkalinity (as $CaCO_3$) and pH data for sites monitored by the Environmental Protection Agency (EPA) during 2019 and 2020 were downloaded from the EPA website and spatially interpolated using Arc GIS 10.5. Additional monitoring sites were also sampled in March 2020 by the LARC team providing interpolations of higher resolution (Fig. 4.1).

Carbon dioxide and bicarbonate

Total alkalinity, pH and temperature values were extracted from the interpolated raster surfaces for all points in the *L. major* dataset and were used to calculate the partial pressure of carbon dioxide in surface water (pCO2(w)) and bicarbonate (HCO_3^-) using the publicly available software package CO2SYS (Pierrot *et al.* 2006) and an interpolation raster was created for data visualisation (Fig. 4.4).

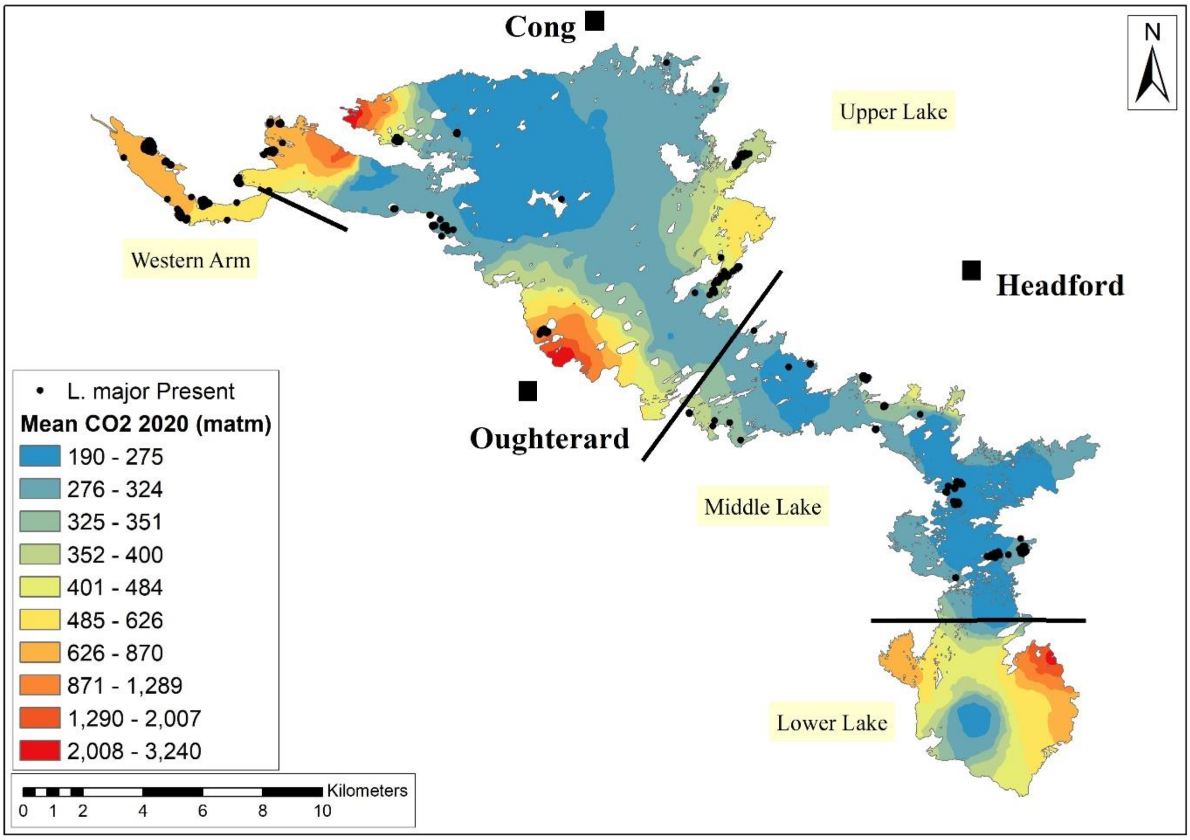


Fig. 4.4. Interpolation of mean pCO2 (µatm) in Lough Corrib, March to October 2020 with *L. major* presence 2019-2020 displayed for reference.

4.2.4 Statistical analysis

Statistical models were used to explore the effect of habitat (fetch length x fetch bearing; depth; hardness; slope; aspect) and environmental (mean temperature; mean Lux; CO_2) variables on *L. major* abundance (%cover). Data exploration (Zuur *et al.* 2010) and statistical analysis were conducted in R and revealed that the data was zero inflated, spatially correlated and that environmental factors displayed non-linear patterns. All habitat and environmental factors were assessed for collinearity using VIF. Alkalinity, pH, pCO_2 and HCO_3^- were highly collinear and so alkalinity, pH and HCO_3^- were excluded from the models, as pCO_2 was considered ecologically most relevant. Model selection was completed using AIC to compare fit for a set of candidate models. Due to the absence of sufficient temperature and light data from 1 m below the surface in 2019, environmental variables were modelled separately using 2020 data only, while 2019 and 2020 data was used for habitat variables.

The effect of habitat factors (fetch length X fetch bearing; depth; hardness; slope; aspect, distance from shore) on *L. major* presence/absence data from 2019 and 2020 were investigated using zero-inflated GLMM's with a binomial distribution and management unit nested within lake basin were included as a random effect using the R package glmm TMB (Brooks *et al.* 2017).

The effect of environmental factors (mean [March-October] temperature[°C]; Light [Lux]; pCO_2 [µatm]) and depth on *L. major* abundance (%cover) 2020 data were investigated using zero-inflated GAMs with beta distribution using REML. A spatial spline with a soap film boundary and knots were used to account for spatial autocorrelation. Analysis was conducted using the R package Mixed Gam Computation Vehicle with Automatic Smoothness Estimation (MGCV) (Wood, 2017) and variables were standardised.

4.3 Results

4.3.1 Lake-wide survey

***L. major* dataset presence/absence**

Survey results showed that *L. major* was absent from the lower lake and Ballindiff Bay. *L. major's* distribution in the middle lake was sporadic with larger isolated pockets occurring in Annaghdown and Clydagh. A relatively low occurrence was also apparent along the northern shore of the upper lake and around the adjacent offshore islands. While the western arm appeared to have a higher level of infestation than elsewhere in the lake (Fig. 4.5).

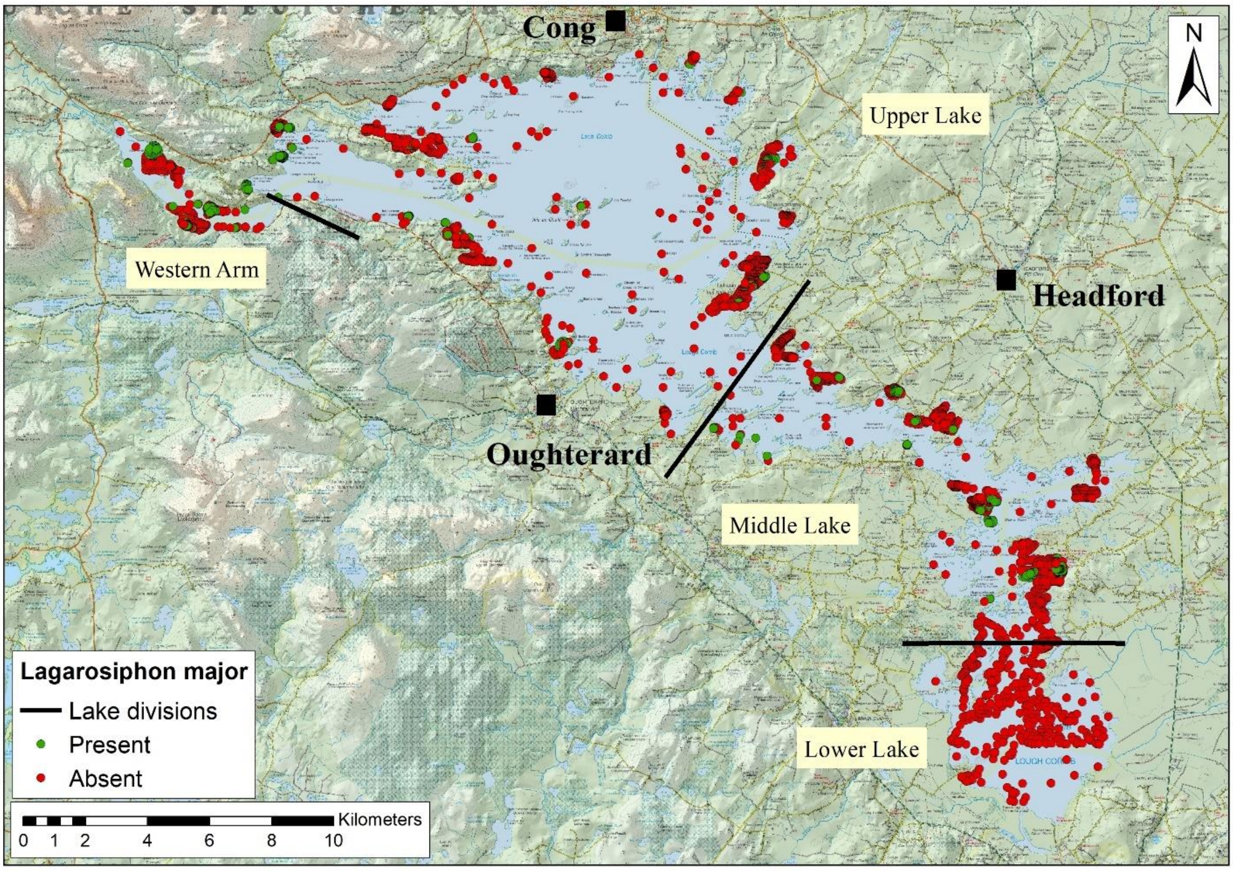
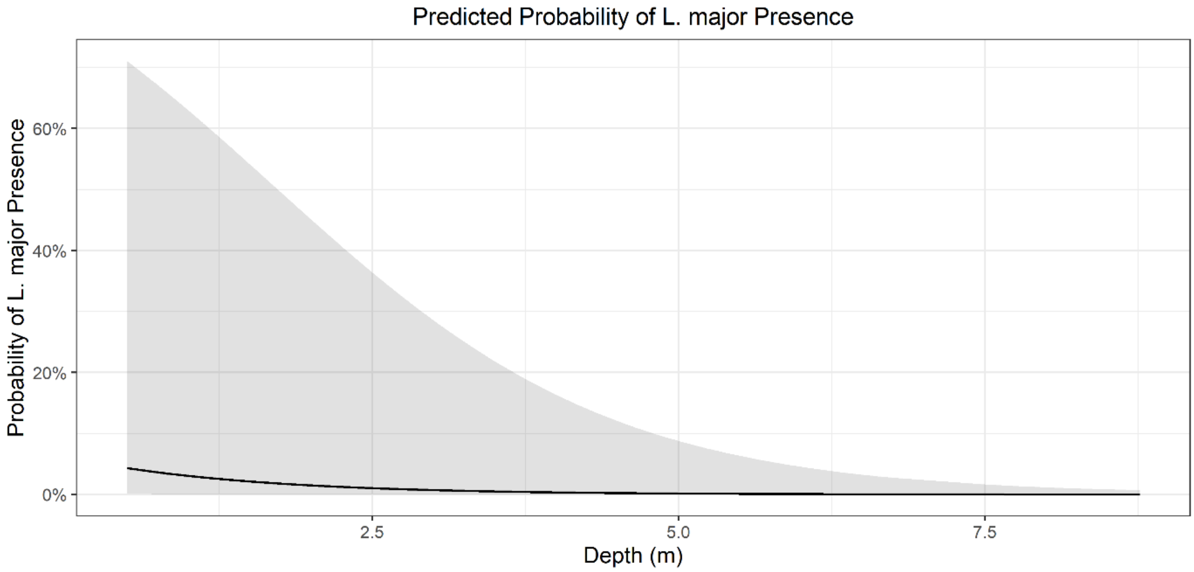


Fig. 4.5. ***L. major*** **presence/ absence (2019-2020).**

4.3.2 Habitat variables

The best fitting model took the following form LagPresAbs ~ Depth + Hardness + Slope + Aspect. Depth and hardness were significant (GLMM *P* <0.001) predictors of *L. major* presence in Lough Corrib (Fig. 4.). Results showed that *L. major* is more likely to be found in shallower water and in areas with soft to medium bottom hardness. The error surrounding estimates is large and reflect *L. major's* highly variable and patchy distribution across the lake (Fig. 4.6).



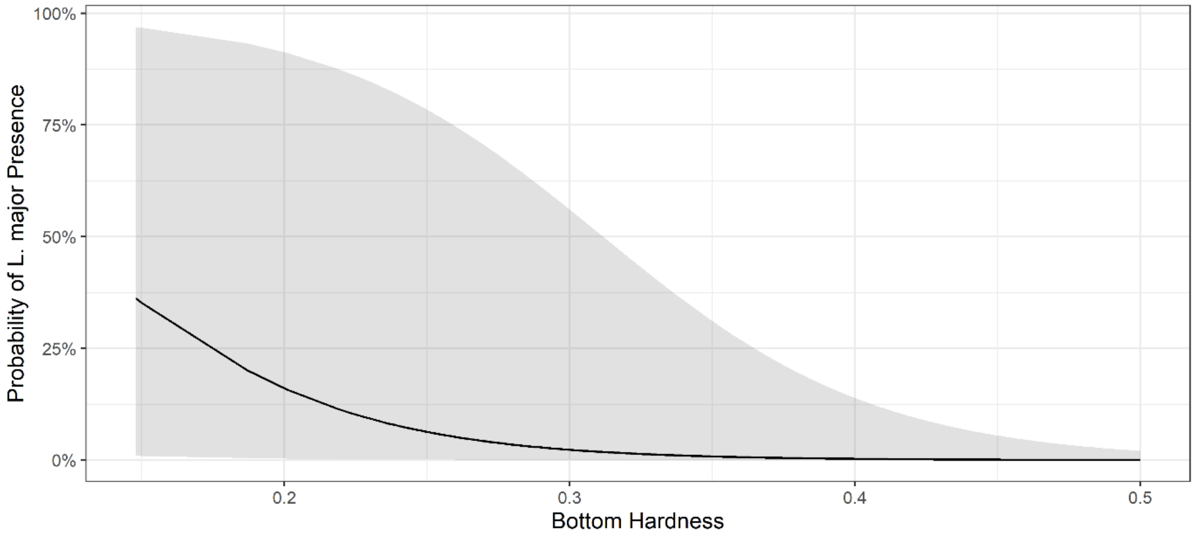
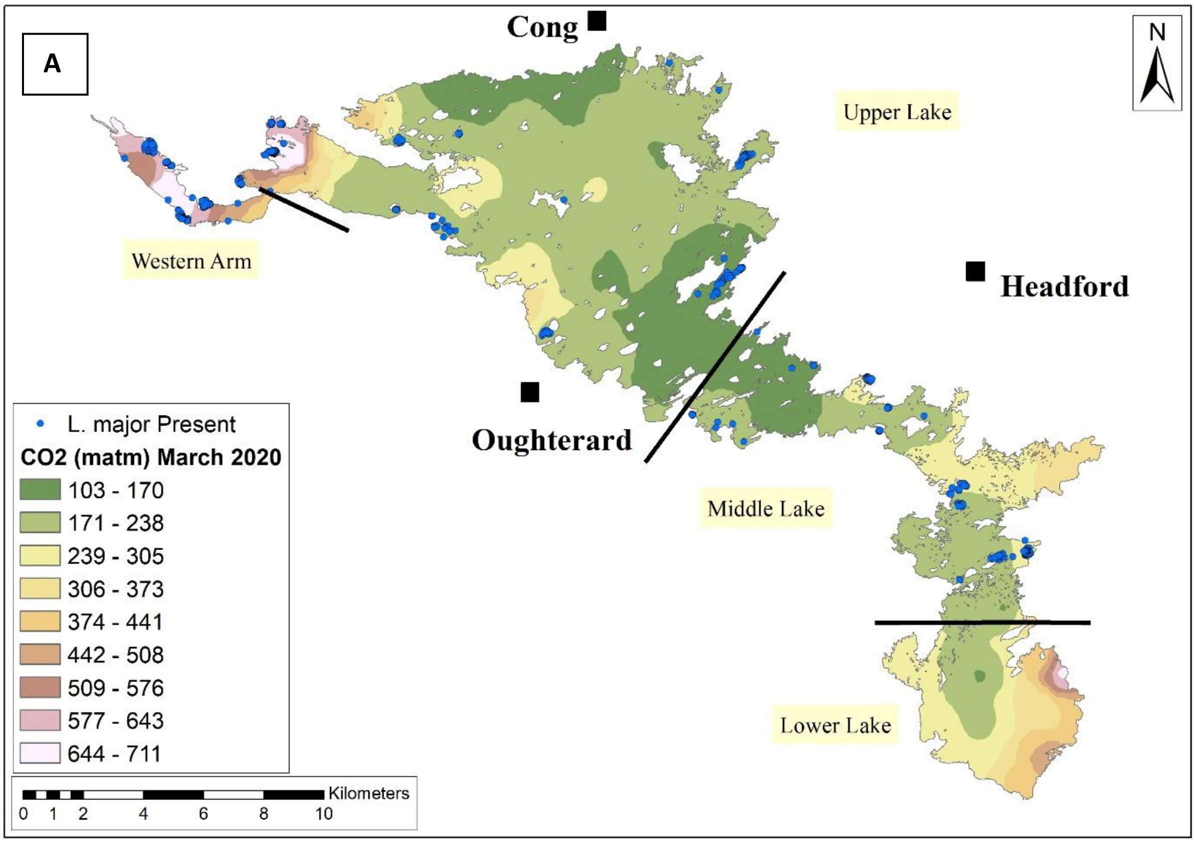


Fig. 4.6. The probability of *L. major* presence across the range of depths and bottom hardness sampled in 2019 and 2020.

4.3.3 Environmental variables

The best fitting model took the following form Lag%Cover ~ s(pCO2) + s(Light) +s(Spatial Co-ordinates). The effect of pCO_2 and light were significant (GLMM P <0.001) predictors of *L. major* abundance in Lough Corrib (Fig. 4.7). Results show that *L. major* abundance is highest at high pCO_2 and low light levels. There were insufficient data to draw conclusions about highest pCO_2 levels at lowest light levels and therefore this region of the graph has no colour. The model explained 31% of the deviance and the spatial co-ordinates did not have a significant effect (GLMM P >0.05). This outcome implies that *L. major* cover varies quite strongly according to some un-measured factors, but that observed cover may reflect the same set of explanatory variables across all sampled sites.



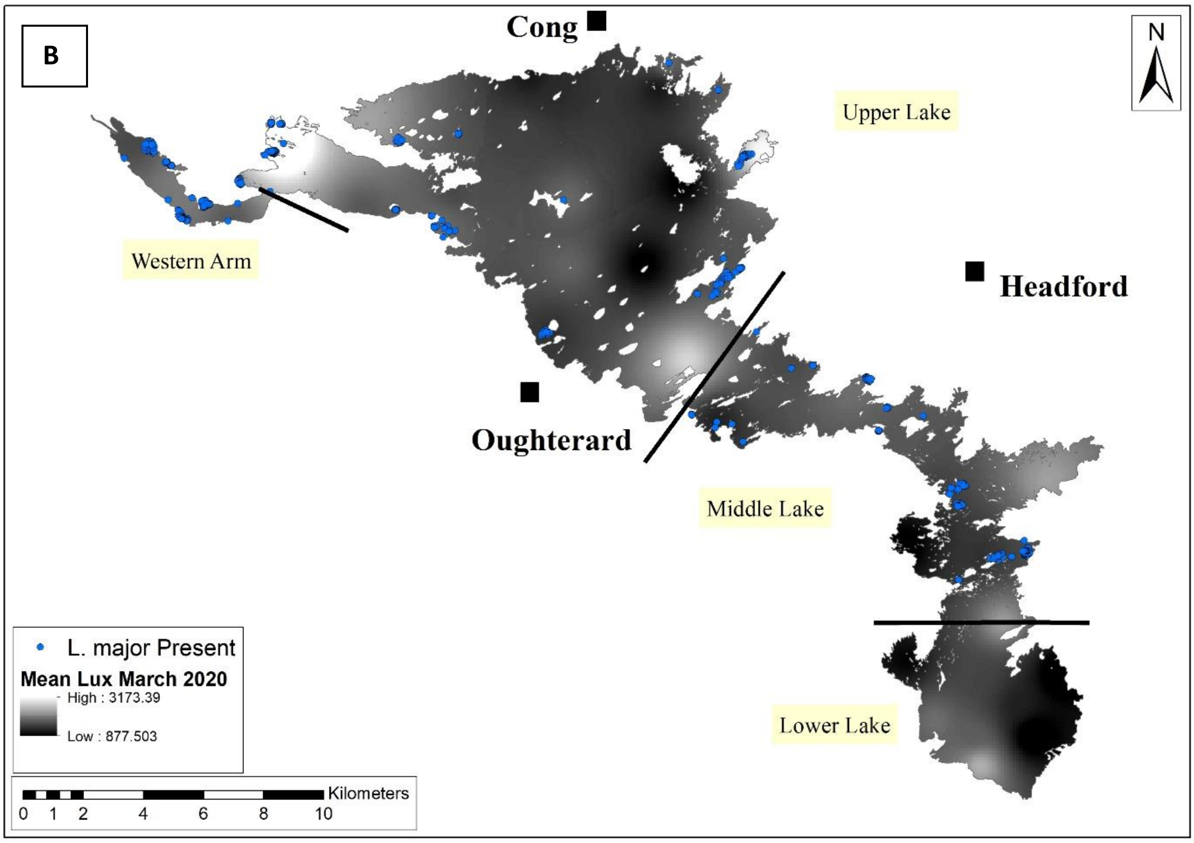


Fig. 4.7. Interpolation of (A) pCO2 (µatm) and (B) Light (Lux) in Lough Corrib, March 2020 with *L. major* presence 2019-2020 displayed for reference.

4.4 Discussion

This study found that *L. major* presence was significantly negatively affected by increasing depth and bottom hardness while fetch (shelter), slope, aspect and distance from shore were not found to be important. The study also found that *L. major* abundance was affected by pCO_2 and light while temperature was not found to have a significant effect. Previous research on Lough Corrib indicated that shelter, silty substrate and depth are important factors that influence *L. major* distribution (Caffrey *et al.* 2011). The effects of pCO_2 and light are newly documented by this study and provide new insights into why *L. major* is more abundant in certain areas in Lough Corrib.

L. major displays high plasticity in relation to light (Riis *et al.* 2010) and can maintain growth under varying light conditions (Hussner *et al.* 2011, 2015). Previous results from Lough Corrib found that *L. major* grows to greater depths where light levels are higher (Morrissey *et al.* 2020). In this study we found that *L. major* was more abundant at lower light levels which contrasts with research in New Zealand where declines were associated with decreases in water clarity (Coffey and Clayton 1988; Wells and Clayton 1991). Possible explanations for the observed trend of increasing *L. major* abundance with decreasing light are 1) competitive interactions e.g., *L. major* can grow to the surface to obtain light 2) control measures are less effective in low light turbid waters and so the higher abundance is a result of differences in control efficacy at different light levels.

The availability of free CO_2, nitrogen and phosphorous often limits submerged aquatic plant growth (Bornette and Puijalon 2011; Andreas Hussner *et al.* 2016; Hussner *et al.* 2015). Hence plants such as *L. major* that can use CO_2 and HCO_3^- as a carbon source may have a competitive advantage over obligate CO_2 users (Bain and Proctor 1980; Yin *et al.* 2017). Indeed differences in HCO_3^- use efficiencies across alkalinities can influence species interactions and distribution (Cavalli *et al.* 2012; Yin *et al.* 2017). For example, *L. major* growing at low alkalinity (typically higher CO_2) exhibited higher photosynthetic rate and bicarbonate use efficiency than *C. demersum*, while the inverse was true at higher alkalinities (Cavalli *et al.* 2012). Earlier research also found that *L. major's* high plasticity under low CO_2 and high pH conditions enabled it to outcompete *C. demersum* but alkalinity was not considered (Stiers *et al.* 2011).

In this study free CO_2 was found to have a significant non-linear effect on *L. major* abundance with peak abundances corresponding with CO_2 levels between 600-800 (µatm). The reason for this non-linear effect is not clear but a positive linear effect has been found elsewhere (Riis *et al.* 2010). This non-linear effect may be due to competitive differences between the various plant communities along the pH, alkalinity, temperature and associated dissolved inorganic carbon gradients. Charophytes which are adapted to low nutrient and high pH and alkalinity conditions are dominant in the Lower lake and Ballindiff Bay where *L.*

major is absent. It is possible that they prevent *L. major* invasion due to their more efficient HCO_3^- use at high pH and immobilisation of phosphorous during the growing season via calcite co-precipitation (Hidding *et al.* 2010; Sand-Jensen *et al.* 2018; Wiik *et al.* 2013). Dense charophytes beds also tend to be associated with areas with high light values. Therefore, it is possible that the reduced abundance of *L. major* from areas where charophytes dominate may also explain the negative correlation we observed between *L. major* and light. However, it is also possible that the absence in these area's is due to poor dispersal, perhaps *L. major* has not yet arrived at these locations. In conclusion, a wider range of factors than those studied here probably control the abundance and distribution of *L. major* in Lough Corrib.

Future research could build on the wealth of data that has been generated during this project. In this study mean values for light, CO_2 and temperature were used. However, CO_2 availability is directly related to pH, alkalinity and temperature which vary on a seasonal, diurnal and episodic basis in lakes (Christensen *et al.* 2013; Sand-Jensen *et al.* 2019). Therefore, it would be worthwhile to investigate the effects of variations over time and explore the effects of maximum and minimum values. Finally, future studies should also incorporate the effects of control and dispersal via boating activities.

5: GENERAL SUMMARY AND RECOMMENDATIONS

Inland Fisheries Ireland continues to support extensive year-round control operations, alongside partner agencies, Office of Public Works, National Parks and Wildlife Service and Galway County Council, to reduce the socioeconomic and ecological burden of the invasive plant, *Lagarosiphon major* in Lough Corrib. An average area of 12.3 ha has been treated annually since 2014 allowing native flora and fauna to re-establish at many sites, restoring the amenity value of previously choked-up bays. The aim of the LARC project (2018 to 2020) was to inform and support the on-going *L. major* management activities on Lough Corrib. This project had five work packages and the findings of these are summarised below.

5.1 Work package 1: Review the literature for recent developments in aquatic invasive aquatic plant species control which may inform L. major control measures

A literature review was carried out to investigate recent international developments in aquatic invasive plant species control, eradication and prevention worldwide. To date, successful *L. major* eradication programmes around the world involved early detection and rapid intervention but have been limited to relatively small waterbodies (<2 ha). Although relatively few new mechanical control methods have been developed in recent times there has been some innovation related to fragment containment methods during and after harvesting/cutting, e.g. bubble curtains and debris collectors (sea bins and skimmer boats). Ultraviolet-c and laminar flow aeration technology are emerging as potential new physical controls methods for aquatic plants and new research is underway to test these technologies. Light exclusion (e.g. jute matting) remains one of the most efficient physical control methods for controlling invasive aquatic plants. Progress has also been made in biological control. Biological control research has focussed on the leaf mining fly *Hydrellia lagarosiphon* and a chironomid midge (*Polypedilum* sp.).

5.2 Work package 2 - Establish the current distribution and extent of colonisation of L. major in L. Corrib

Lake-wide *L. major* distribution results from four different sampling phases show that *L. major* progressed through a rapid range expansion when it was first introduced into Lough Corrib. Initially, it was mainly distributed throughout the western arm, upper lake and northern section of the middle lake. Since 2010-2012, it has been spreading slowly towards the lower lake. Extensive sampling carried out in 2019 and 2020 revealed that there are still no records of *L. major* in the lower part of Lower Lough Corrib; however the southern edge of its distribution (SU15 - Annaghdown) is approaching this boundary and growth is particularly good in some of the most southerly sites. During 2020 an estimated total of 12.3 ha of large *L. major* infestations (>50m^2) were present in five survey units. An additional ninety-eight relatively small

(<50m^2) isolated patches were also recorded across ten survey units. The largest infestation was recorded in SU1, the Maam River area and Drumsnauv Bay, while the largest single area infestation was present in Annaghdown. Comparison with the 2013 distribution shows that the area of infestation has decreased, but the distribution of *L. major* has widened across the lake. At present, it appears that the annual control efforts undertaken on the lake are keeping the infestations at manageable levels and preventing the spread of the plant to the lower lake. However the lower lake area is continually at risk from infestation due to vectors pathways.

5.3 Work package 3: Determine the influence of habitat and environmental factors on L. major in L. Corrib

L. major exhibits a wide range of variability at individual sites in its capacity to establish itself. It also displays a varied response to control efforts throughout the lake (e.g. some sites require annual control efforts and others do not). The mechanisms underpinning this variability are not understood but it is likely that habitat type and environmental factors play an important role. Filling this knowledge gap may identify more effective control strategies and improve predictions of *L. major* distribution.

Light, temperature, depth, substrate type and the availability of nutrients and carbon are factors affecting plant growth, but these variables vary substantially throughout the lake. Large amounts of environmental and habitat data were collected, processed and analysed during 2019 and 2020 to investigate their influence on *L. major* in Lough Corrib at both local and lake-wide scales. Analysis revealed that *L. major* presence was negatively affected by increasing depth and bottom hardness (i.e. *L. major* is more likely to be found in shallow water with soft to medium substrate) while fetch, slope, aspect and distance from shore were not found to be important. *L. major* abundance was found to be affected by both CO_2 and light (i.e. higher abundance in areas with high CO_2 and low light levels) while temperature was not found to have a significant effect. The effects of CO_2 and light are newly documented by this study and provide new insights into why *L. major* is more abundant in certain areas.

5.4 Work package 4: Develop and trial new approaches for surveying L. major.

A range of new approaches for surveying *L. major* in Lough Corrib were trialled between 2018 and 2020. Traditional sampling methods using direct observation can be time and resource intensive and can carry an element of health and safety risk. This project found that a range of modern sampling techniques could be implemented as they will increase the accuracy and efficiency of *L. major* data collection while also providing much needed quantitative data.

Low-cost sonar with simultaneous ground truth sampling and recorded using ArcGIS survey tools was identified as the most reliable and efficient survey method. Low-cost sonar units represent value for money and the largely automated data processing is free of charge through an online portal once the data owner agrees to “open access”. The project also found that underwater imagery generated using a high-definition camera with live feed and geo-referencing ability was superior to grapnel sampling for ground truthing as the latter was biased towards certain species. UAVs proved useful for mapping *L. major* when the weed was at the surface in locations unsuitable for the sonar boat, i.e. rocky and shallow areas. UAVs also proved useful in identifying the exact locations of jute mats in clear shallow waters. However calm dry weather is required and they are limited to a certain range. They also proved useful for assessing fragmentation generated by harvesting and control methods. The other survey methods tested (e.g. UAV, satellite, underwater imagery) were also useful on occasions where the use of sonar was not possible or practical.

A pilot study was conducted with the Irish Centre for High-End Computing (ICHEC) to investigate the application of using Sentinel 2 multispectral satellite imagery to map *L. major* in Lough Corrib at the lake-wide scale. The study found that that this method has potential for mapping the macrophyte at the lake-wide scale but more areal/polygon data (presence and absence of *L. major* and other common macrophyte species) is required to improve the algorithm and verify its usefulness. Additional research indicated that sonar should be used to gathering this areal data.

Electronic data collection forms were found to greatly increase the accuracy and efficiency of data collection and suitable forms have been created and successfully tested for research and management purposes.

5.5 Work package 5: Develop a concept design for semi-automated weed control

Discussions with the Oirbsean control team in 2018 revealed that there was a significant amount of manual handling associated with the mechanical cutting operations during the winter months. Large volumes of harvested weed must be lifted from a boat onto shore manually. There are also regular mechanical issues with the existing weed cutting boats deployed on the lake to control *L. major*. This has resulted in increased maintenance costs and several down days.

To address these issues discussions were held with engineers in University College Dublin to explore how the more laborious aspects of this work could be semi-automated. From these discussions it became apparent very quickly that a suitable solution would not be readily found without significant investment and therefore was beyond the scope of the project budget.

However, during June/July 2019 the control team commenced a trial of a Berky Aquatic Weed harvester 6450. This harvester has a conveyor belt and a large storage capacity. The trial was undertaken in Drumsnauv Bay, in Upper Lough Corrib where it has not been possible to carry out existing control methods. The harvester rapidly cleared the surface canopy but the benefits were temporary and active regrowth was observed 21 days after cutting. Patches of regrowth were also spotted at the surface in some areas of the bay within three and a half months. Fragmentation, which is a common feature in macrophyte control operations, was observed during the trial. The fragment size and percentage area coverage showed that cutting using this type of weed harvester assessment can pose a risk to surrounding areas suitable for *L. major* colonisation unless stringent containment measures are in place.

Underwater imagery showed that the blades provided a clean cut. Aerial imagery and chemical analysis showed that cutting caused re-suspension of sediment, again a feature of many mechanical control operations. Analysis of water quality parameters over a short time scale post-cutting indicated that weed harvesting had a temporary effect on turbidity, total phosphorous and chlorophyll *a* in the bay. Finally, manual handling issues were improved but not resolved by the harvester. It was concluded that, harvesting should only be completed during calm weather and to further minimise risk, containment methods should be able to withstand poor weather conditions.

5.6 Overall recommendations from the project

5.6.1 Control efforts

1. At present, it appears that the annual *L. major* control efforts undertaken on the lake are limiting the spread of the plant within the lake, but the plant is moving slowly south towards the lower lake. Therefore control efforts should be maintained to protect the lake from the invasive macrophytes negative impacts until a better control solution (e.g. biocontrol, UV light, etc.) has been developed. There are several heavily infested sites in the Maam and Anaghdown areas and the control team should continue to prioritise these for ongoing control works where possible.

2. The implementation of suitable control measures in many parts of the lake is difficult, particularly in the Maam area where the largest infestation was recorded during 2020. Fast water currents, weather and the presence of rock all impede the successful control of *L. major* (e.g. *L. major* embeds between rocks and makes the cutting of the weed with the trailing v blades and subsequent laying of jute matting almost impossible). Therefore it is important to continue to monitor the international literature for new methods of controlling *L. major* as an alternative method is required particularly for these difficult areas.

3. The control team has also experienced numerous issues with the two weed cutting boats deployed on the lake. This has caused considerable downtime during 2019 and 2020 and has shortened the window for weed cutting during the erect phase in winter. In a lake the size of Lough Corrib (16,500 Ha) it is extremely important that the weed cutting boats are safe and usable when required for deployment. Therefore a review of the efficacy of the weed cutting boats and funding for this area is required to necessitate efficient ongoing control works.

4. The installation of low-cost sonar units on the aluminium boats used by the control team should be considered to improve reporting. This would also allow quantitative sampling to be conducted equally effectively in clear and turbid waters while also increasing the safety of the crews by uploading a Lough Corrib navigation chart onto the unit.

5.6.2 Monitoring the distribution of *L. major* in Lough Corrib

5. Dividing the lake into 21 survey units was found to be a useful framework for prioritising and planning surveys. This method could also be used to plan and track containment and control measures. For example, SU1 (Maam area) is the most highly infested area and should continue to be prioritised for containment and control although it is recognised that these works are extremely difficult in this area.

6. New survey methods identified during this study could be used for ongoing annual monitoring and assessments, i.e. low-cost sonar with simultaneous ground truth sampling and data recording using ArcGIS survey tools was identified as the most reliable and efficient survey method. Underwater imagery generated using a high-definition camera with live feed and geo-referencing ability and UAVs is also recommended for ground truthing the sonar surveys.

5.6.3 Biosecurity and stakeholder engagement

7. As the invasive plant is still abundant in certain areas, stakeholder information, education and biosecurity should remain a priority. It is recommended that all information signage be reviewed at existing locations and upgraded where necessary. Biosecurity signage should continue to remind water users of the risk from invasive species and to check and clean their equipment when moving from one area of the lake to the other.

8. Consideration should also be given to in-lake signage to highlight high risk areas such as Maam and Annaghdown.

9. This work could also be complemented by use of social media and or websites to remind lake users to exercise caution and employ preventative measures to reinforce public awareness.

10. This could also be accompanied by an annual education campaign to reinforce the message to existing and new lake users (e.g. many lake users may not know that plant fragments, chopped up by propellers, snagged on paddles, can take root and start new infestations. These fragments are easily transported throughout the lake and therefore pose a risk to the rest of the lake).

11. Boat back-up stations have been developed in Lake Tahoe, USA, for lake users to disinfect their boat prior to moving to other areas within the lake to reduce invasive plant fragments being carried further into the lake. Bubble curtains are used in busy channels in the same lake to contain fragments. Skimmer boats are also used to collect floating plant fragments. A feasibility exercise should be considered to review the applicability of similar methods on Lough Corrib particularly in high-risk areas (e.g. Maam and Annaghdown).

5.6.4 Data sharing and collection

12. Prior to 2018 quantitative control and distribution data was unavailable in a spatial or quantitative format and therefore it was difficult to assess the efficacy of control measures over time. It is extremely important that all data associated with control measures and ongoing survey work on Lough Corrib is recorded in a geodatabase. Data sharing, collection and access has been improved by storing all available *L. major* distribution and control data in an integrated GIS database on Arc GIS online. Improvements in data collection can be made simply and immediately by using the Survey123 or Collector forms created by the LARC project to collect all control and ground-truth data. It is recommended that the control team use these electronic data collection forms for more efficient tracking of control locations and any new sightings to provide managers with accurate easily accessible up to date information and to negate the risks of setbacks in the future if contractors change. Dashboard metrics can be created for each of the survey units created here for ongoing reporting and monitoring. This approach will ensure that all required information is collected in a standardised and accurate way and will future proof the programme. Data collected using this method also increases the speed and ease at which data can be made available to those managing or researching *L. major*.

13. Consideration could also be given to the development of a citizen science application that allows members of the public to record *L. major* sightings. Integration of this data into the GIS database would further improve the collective management of *L. major* and the appropriate deployment of resources.

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