Lagarosiphon Research Lough Corrib (LARC) Interim Report 2018-2019

IFI/2020/1-4520

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Lagarosiphon major Research on Lough Corrib (LARC)

Interim Report 2018-2019

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CITATION: Morrissey, E., Meade, R., Matson, R., McCarthy, E. and Kelly, F.L. (2020) *Lagarosiphon major* Research on Lough Corrib. Interim Report 2018-2019.

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Acknowledgements

The authors wish to gratefully acknowledge the help and co-operation of the former Inland Fisheries Ireland (IFI) Galway/Ballina Director Dr. J.J. Connelly (now retired) and the current Director Mr. Francis O' Donnell. The authors also wish to acknowledge the help and co-operation of all their colleagues in Inland Fisheries Ireland and Oirbsean staff, Helen Moran, Francis Clancy and Matthew Kelly. Finally the authors also acknowledge the assistance of Dr. Joe Caffrey of INVAS Biosecurity and Evan O'Keeffe (UCD).

The authors would also like to acknowledge the funding provided for the project from the Department of Communications, Climate Action and Environment for 2019.

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Executive Summary

Lagarosiphon major (Ridley) is an invasive aquatic species (IAS) of Union Concern (EU Regulation 2016/1141) that was first recorded in Lough Corrib in 2005. Since that time control operations have been required to stop dense canopy formation closing bays to anglers and other water users. Over the last four years approximately 12.3 ha/annum have been treated. These treatments play an important role in protecting the lake and preventing further spread.

This report summarises the scientific work carried out by Inland Fisheries Ireland (IFI) during 2018 and 2019 to inform and support on-going *L. major* management activities in Lough Corrib. The main aims of the project are to review recent international developments in invasive aquatic plant species control; develop and trial new approaches to improve surveying and monitoring; establish the current distribution and extent of colonisation of *L. major* in the lake and to determine the influence of habitat and environmental factors on the establishment and persistence capacity of the invasive plant in the lake.

An international literature review detailing developments in aquatic invasive plant species control, eradication and prevention worldwide has been completed. Successful invasive species eradication programmes around the world involve early detection and rapid intervention but have been limited to relatively small waterbodies (<2 ha).

Control operations are broken into four categories (i.e. mechanical (harvesting), physical, chemical and biological). Although 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) still remains one of the most efficient physical control methods for controlling invasive aquatic plants. Progress has also been made in the area of biological control. Research has focussed on the leaf mining fly *Hydrellia lagarosiphon* and a chironomid midge (*Polypedilum* sp.). However rigorous testing is still required to evaluate any undesired non-target effects of each method.

Reinforcing public awareness can help prevent or slow the spread of *L. major*. The provision of signage on the water in high impact areas reminding water users to check and clean their equipment when moving from one area of the lake to the other would be useful. 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. Recent research has shown that immersion of equipment in disinfectants has shown variable results and should not be considered completely effective against *L. major;* while applying steam to equipment for 30 seconds appears to be an effective treatment.

A range of new approaches to surveying *L. major* were trialled during 2018 and 2019. Traditional sampling methods using direct observation can be time and resource intensive and can carry an element of health and safety risk. Several innovative solutions are now available, including remote sensing technologies and electronic data collection applications. A multi-method remote sensing survey approach was found to be the most efficient method of mapping the distribution of *L. major* in Lough Corrib. This method combines underwater imagery with hydroacoustics, UAV's (Unmanned Aerial Vehicle i.e. drone) and multispectral satellite imagery. Electronic data collection forms were also developed to capture on-site data. This has increased data availability, accuracy and collection efficiency. Underwater imagery was a useful tool for observing areas that would otherwise require divers. Hydroacoustics was useful for mapping *L. major* and its habitat when the plant was submerged. Satellite imagery and aerial drones (UAV's) were effective when the plant was at the surface.

The current and historical data on *L. major* distribution in Lough Corrib were collated and mapped. Most areas suitable for establishment were colonised rapidly between 2005 and 2008. Since that time *L. major* has been widely distributed throughout the western arm, upper lake and the northern section of the middle lake. Its distribution is slowly edging southwards and it grows very well in some of the more southerly sites. To date *L. major* has not been recorded in the lower lake.

Data was gathered on a wide range of habitat and environmental variables to investigate their influence on *L. major* in Lough Corrib at both local and lake-wide scales. The work completed to date indicates that alkalinity, pH and nutrients may be important factors that have slowed *L. major's* expansion into the lower lake. The collection of additional data on macrophyte distribution and important variables such as pH, alkalinity, temperature and light will facilitate the development of statistical models in 2020.

A weed harvester was trialled in a bay of Lough Corrib unsuited to existing control methods during June/July 2019. The harvester rapidly cleared the surface canopy but active regrowth was observed 21 days after cutting and patches of regrowth were observed 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 a weed harvester can pose a risk to surrounding areas suitable for *L. major* colonisation, unless stringent fragment 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 is 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.

The next stage of this scientific work will involve surveying additional sites and modelling the influence of habitat and environmental factors on *L. major* in Lough Corrib. Distribution mapping of *L. major* will also continue and the use of multispectral satellite imagery to map the distribution will be investigated further.

As the invasive plant is still abundant in certain areas, stakeholder information and biosecurity is still a priority. It is recommended that all relevant signage be upgraded at existing locations and additional signage be installed, particularly in strategic areas. Consideration should also be given to in-lake signage to highlight problem areas. This work could be complemented by use of social media and or websites to remind lake users to exercise caution and use preventative measures.

It is also recommended that all control activities and any new sightings should be recorded in electronic GIS based forms so that information is easily accessible to those managing *L. major* (for planning and control purposes).

1: Introduction

1.1 Background

Lagarosiphon major (Ridley) or curly-leaved waterweed is an invasive aquatic plant species (IAS) native to southern Africa that has invaded Lough Corrib. The plant 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 six metres 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 when fragments of the plant become detached and float away (Redekop *et al.* 2016).

IAS management requires effective regulation for; spread prevention, early detection, rapid response eradication programmes and long-term management/control where eradication is impossible (Shaw *et al.* 2016; Wittenberg and Cock 2005). The European Union (EU) has adopted legislation requiring member states to prevent and manage the introduction and spread of listed invasive species (EU Regulation No 1143/2014 of the European Parliament and of the Council on the prevention and management of the introduction and spread of invasive alien species). A key instrument underpinning this regulation is Article 4 which requires the adoption of a list of IAS of Union concern. This list sets out priority species that require action to prevent, minimise or mitigate their adverse impacts. *L. major* is included in this list (Commission Implementing Regulation 2016/1141 of 13 July 2016 adopting a list of invasive alien species of Union concern pursuant to Regulation (EU) No 1143/2014 of the European Parliament and of the Council). Other key instruments of Regulation No 1143/2014 include Articles 16 & 22 which specifically encourages the use of early-detection system and Article 17 that calls for rapid eradication and long-term mitigation and control mechanisms.

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 closing large bays in the upper and middle lake (Caffrey *et al.* 2011). 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 highly invasive plant from over 90% of the previously infested areas, leaving 9 ha in need of maintenance in January 2013 (CAISIE 2013). Despite this *L. major* spread, expanding its range and the number of sites in need of maintenance; by September 2013 31.31 ha were considered in need of control (Millane *et al.* 2013).

Eradication of *L. major* is virtually impossible in a lake the size of Lough Corrib (18,240 ha) but the on-going management efforts have so far shielded 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 (CAISIE 2013; Geomara, 2016, 2017; Oirbsean Ltd. 2018;). Significantly, *L. major* has not yet been recorded in the lower section of Lough Corrib where extensive areas have been identified as high risk due to its shallow nature (Caffrey *et al.* 2011; Millane *et al.* 2013).

1.2 Study area - Lough Corrib

Lough Corrib is the largest lake in the Republic of Ireland (18,240 ha). The lake is part of a Special Area of conservation (SAC) and is designated as a Special Protection Area (SPA) and a Ramsar Convention site (i.e. a wetland of significant value for nature). It is the primary source of drinking water for the surrounding area, including Galway City.

The lake varies significantly from north to south. The north has low alkalinity oligotrophic water and is typically characterised by less weathering geologies e.g. granite and sandstone. In contrast, the shallow southern section has high alkalinity water underlain by carboniferous limestone. The lake flora also transitions from an oligotrophic *Isoetes* sp. dominated flora in the western arm to mesotrophic Charophyte dominated flora in the southern basin (Krause and King 1994). Consequently, the lake can be divided into four sections based on the topographical features and floral communities (Figure 1.1).

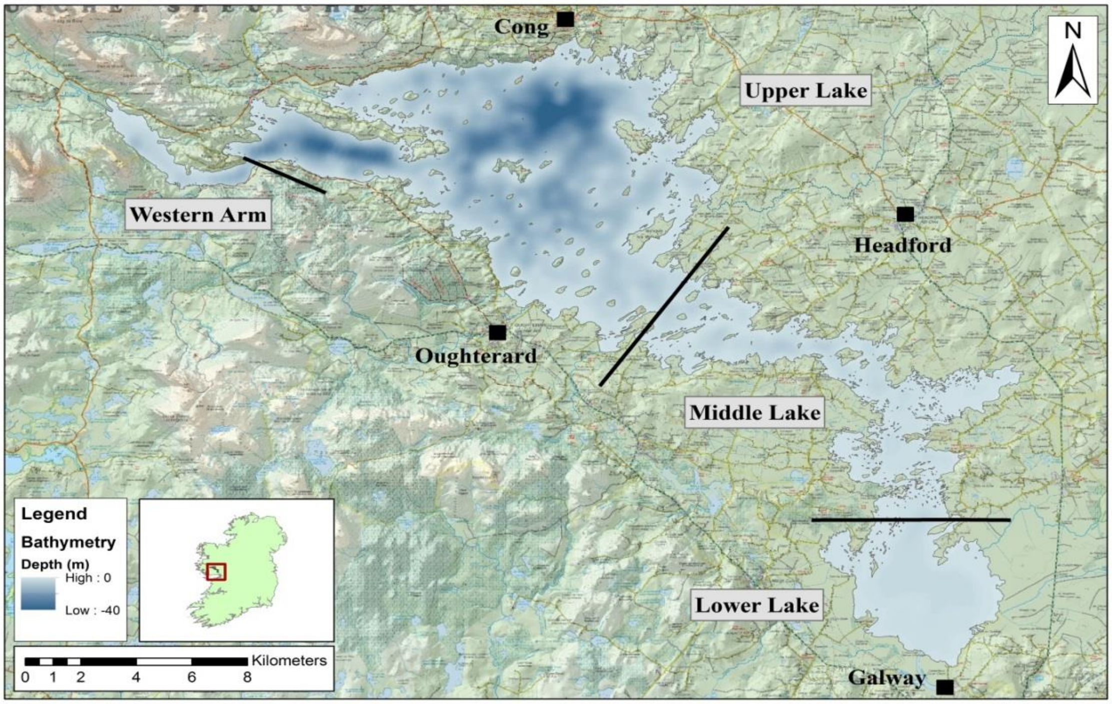

Figure 1.1. Lough Corrib divided into four sections (according to King and Krause, 1994) the western arm, upper, middle and lower lake.

1.3 Project Aims

This new scientific project was initiated by IFI in 2018 to inform and support the on-going *L. major* management activities on Lough Corrib. The project has five work packages with specific aims:

1. Literature review – review recent developments and advancements in invasive aquatic plant species control which may inform development and refinement of control measures.

2. Develop and trial new approaches to enhance surveying and monitoring of *L. major*.

3. Establish the current distribution and extent of colonisation of *L. major* in L. Corrib to inform on-going and future control measures.

4. Determine the influence of habitat and environmental factors on the establishment of *L. major* in Lough Corrib.

5. Develop concept design for semi-automated weed control (funding dependent).

This report summarises the scientific work carried out on the project by the IFI research team during 2018 and 2019.

2: Review of Recent Developments in Invasive Aquatic Plant Species Control & Eradication Worldwide

2.1 Introduction

Invasive alien species (IAS) are a major threat to natural systems causing unprecedented biodiversity loss and imposing considerable economic burden (Dudgeon *et al*. 2006; Gallardo *et al*. 2016; Pyšek *et al*. 2012). Globally, 1,517 different IAS span 243 countries/territories and fifty-two invasive aquatic plant species have been found in 110 non-native countries (Turbelin *et al.* 2017). Ninety-six alien aquatic plant species have been reported in Europe (Hussner 2012). The full economic costs of biological invasions include the direct damage and control costs, alongside the negative effects of invasions on host ecological and socio-economic systems (Pimentel *et al.* 2001). The annual cost of monitoring, eradication, control and impact mitigation alone was estimated at €12.5 billion in the EU (Kettunen *et al.* 2008) and US$1.4 trillion globally (Pimentel *et al.* 2001). Management options (eradication, control and prevention) for a particular problem are dependent on the target species, characteristics of the lake and the management goals (e.g. reduction in biomass for lake users or restoration of native aquatic plants).

2.2 Eradication

Eradication involves the "removal of every individual and propagule of an invasive species so that only reintroduction could allow its return" (Zavaleta *et al.* 2001). Eradication typically provides the best chance for native biodiversity recovery (Zavaleta *et al.* 2001). Successful eradication programmes share common traits: the biology of the target species is well known (Anderson 2005), a small invasion area (Gherardi and Angiolini 2009; Mack *et al*. 2000), eradication procedures begin quickly upon detection (Mack and Lonsdale 2002; Simberloff 2008), sufficient resources are readily available (Anderson 2005; Mack *et al.* 2000) and post-eradication surveys to detect missed, or newly settled individuals (Anderson 2005; Mack and Lonsdale 2002; Simberloff 2008).

Globally, there has been a number of successful invasive aquatic plant eradication programmes documented in relatively small waterbodies (<1.5 ha). The tropical aquatic invasive weed *Salvinia molesta* was eradicated from a 0.6 ha pond in South Carolina, USA, by hand picking and herbicide application (Mack and Lonsdale 2002). An invasive marine seaweed *Caulerpa taxifolia* was eradicated from two locations in a Californian Lagoon, covering approximately 1 ha and 0.1 ha respectively within two years.

Containment and treatment involved aquatic herbicides and light exclusion (Anderson 2005). New Zealand has had several successes, including the national eradication of aquatic species *Zizania palustris*, *Menyanthes trifoliata* and *Pistia stratiodes* and the local eradication of *Eichhornia crassipes* and *Salvinia molesta* (Mack and Lonsdale 2002). *L. major* was also successfully eradicated from five shallow ponds in New Zealand with a maximum area of 1.4 ha using the aquatic herbicide, endothall (Wells *et al.* 2014; Wells and Champion 2010). To date there are no reports of *L. major* or other invasive aquatic plants being successfully eradicated from waterbodies larger than 2 ha.

Where eradication fails, the goal becomes keeping the species at acceptable levels via maintenance control (Adams and Lee 2007; Mack *et al.* 2000).

2.3 Control

The control of aquatic invasive plant species can be broken down into four main categories; mechanical, physical, chemical and biological (Charudattan 2001). Mechanical involves harvesting; physical involves manipulation of the physical environment; chemical uses herbicides; and biological involves the use of a natural enemy or pathogen (bio-control).

Effective control strategies target a weak link in the plant's life-cycle (Buhle *et al*. 2005). Two main growth phases, an *erect phase* and a *collapsed phase,* were identified for *L. major* in Lough Corrib (Caffrey *et al.* 2008). The erect, canopy-forming phase typically occurs from October to April. During this *erect phase* the stems are buoyant and susceptible to mechanical cutting with trailing V-blades accompanied by harvesting. *L. major* enters its *collapsed phase* from May to September. Stems are significantly less buoyant and collapse to cover the lake bed and block light from reaching the plants beneath. During the *collapsed phase,* the plants are susceptible to hand-picking and covering, using a layer of jute matting. This is a biodegradable geotextile that excludes light to kill *L. major* and enable the re-establishment of native plants. Jute matting is particularly effective at sites where recent mechanical harvesting takes place (Caffrey *et al.* 2010).

2.3.1 Mechanical control

Mechanical harvesters and cutters

Weed cutters that cut but don't simultaneously remove plant material from the water are the tool most commonly used to manage invasive plants in Europe (Zehnsdorf *et al.* 2015). Weed cutters typically operate deeper than mechanical harvesters. Trailing V-blade cutters are considered most effective as they cut the plant at its base, and in some cases completely uproot the plants (Hussner *et al.* 2017; Zehnsdorf *et al.* 2015). Cutting and harvesting alone, however, will not clear an area of invasive plants. In Lough Corrib, heavily infested areas unsuited to V-blade cutting may benefit from mechanical harvesting, especially, where harvesting cuts near the plant's base, making secondary treatment with jute matting possible.

Weed harvesters are large machines that simultaneously cut and collect aquatic weeds. In general, harvesters remove the top of the plant, with most cutting to a depth of 1.8 m (Caffrey *et al*. 2011). Harvesters can quickly clear dense infestations but invasive plants can grow back rapidly, displaying higher growth rates than plants in unharvested areas (Chisholm 2006; Greenfield *et al.* 2004). Consequently, harvesting may have to be repeated two or three times in a growing season (Chisholm 2006).

Mechanical cutting and harvesting generate viable fragments and so fragment containment is vitally important. Traditionally hand and containment nets have been used to gather and prevent fragment spread during harvesting. Recent innovations in this area include the use of bubble curtains and debris collectors (e.g. sea bins and skimmer boats) in Lake Tahoe, USA (Sierra Ecosystem Associates 2018). Bubble curtains operate by creating a barrier of bubbles deployed by a series of hoses on the lake bed, fed by an on-shore air compressor. When set out in a "V" formation across a channel, the bubbles direct fragments to the edges where they are easily collected (Plate 2.1).

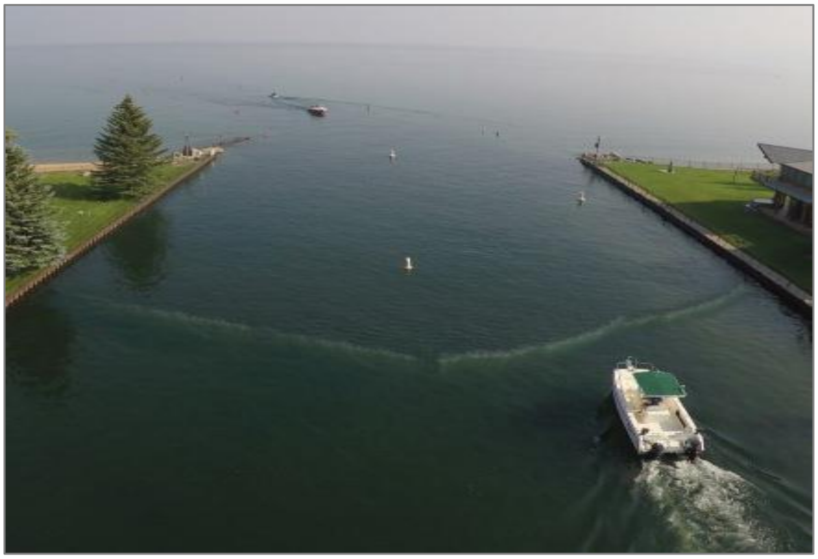

Plate 2.1 Bubble curtain in a "V" formation across a navigation canal, Lake Tahoe, USA (source: keeptahoeblue.org)

A clear benefit of this approach is that it does not impede boat movement, including harvesters which may need to leave the treatment area to unload. In Lake Tahoe, a range of debris collectors and skimmer boats are also used to gather fragments (Sierra Ecosystem Associates 2018). Powered collectors work by pumping surface water and fragments through a container that retains the debris. Unfortunately, active collectors require calm conditions and a continuous power supply to operate effectively (Sierra Ecosystem Associates 2018). Unpowered collectors typically consist of screened containers positioned to intercept debris flowing past, but these require flowing water.

Manual Harvesting (Hand picking)

Manual harvesting involves removing and collecting the entire invasive plant, including the roots by hand. It is highly selective and has minimal environmental impact. Hand-picking is typically time and labour intensive and so it is generally only feasible for small patches or along the perimeter of larger infestations that have been treated using other methods (Simberloff 2003). However, it has also been used to achieve whole-lake control of Eurasian watermilfoil (*Myriophyllum spicatum*) in a large lake (1912 ha) in the USA at enormous expense (Kelting and Laxson 2010).

Rotovation/Rototilling

Rotovation or rototilling uses rotovator heads with spinning blades that break though the sediment, damaging and dislodging the plants root system. Rotovation has been tested on aquatic macrophytes with some success but its application on *L. major* was considered costly and ineffective compared to other control methods (Chisholm 2006). This method is also considered unsuitable for many locations in Lough Corrib where rocks and other obstacles would likely interfere with its use. Fragment generation and water quality issues due to sediment upheaval are also associated with this control method (Gibbons and Gibbons Jr 1988; Waterstrat and Lyon 2013). There have been no recent developments reported in this area.

Suction dredging

Suction dredging uproots aquatic plants using a powerful suction pump. Plant material is then discharged into a collection vessel while the water and sediment are released back into the waterbody (Greenfield *et al.* 2004). Plants are removed with their root minimising the potential for re-growth and spread. This method is suited to small isolated patches of weed, where minimal plant fragmentation is necessary (Alexander *et al.* 2008). It is also effective in areas with obstacles such as rocks, as these can be worked around. However, hard or compact substrates impair its use. The application of suction dredging to *L. major* control has shown varying degrees of success in other jurisdictions, with re-establishment times ranging from two months to three years (Chisholm 2006). Suction dredging is regarded as a costly control measure, in comparison to herbicide or mechanical cutting and generates significant turbidity and nutrient re-suspension (de Winton *et al.* 2013; Greenfield *et al.* 2004) .

Hydro-Venturi (water jets)

Hydro-Venturi ventilation is a new tool that uses water jets to dislodge submerged plants, including the roots, from soft sediments. Dislodged plants float freely to the surface where they are gathered. This methods has been successfully used to control *Cabomba caroliniana* and *Myriophyllum heterophyllum* in The Netherlands (Dorenbosch and Bergsma 2014; Van Valkenburg *et al.* 2011). The method is particularly suited to fragile plants but it is time consuming and can generate high levels of turbidity (Hussner *et al.* 2017).

2.3.2 Physical controls

Light exclusion

Benthic barriers that exclude light have been successfully used to manage invasive weeds in lakes around the world (Hoffmann *et al.* 2013; Hussner *et al.* 2017). Biodegradable jute matting is being used to control *L. major* with great success in Lough Corrib (Caffrey *et al.* 2010). A key advantage of this method is that it allows native plant communities to rapidly re-establish (Caffrey *et al.* 2010; Hofstra and Clayton 2012). Experiments have shown that efficacy can be affected by mat density (Hofstra and Clayton 2012). There have been no new developments in benthic barriers since that time. Light exclusion can also be achieved by placing non-toxic light absorbing dyes into shallow still waters such as ponds. To date this method has not been effective in controlling aquatic invasive plant species (Hussner *et al.* 2017).

Ultraviolet light

Ultraviolet-C (UVC) is emerging as a potential new control method for aquatic plant control. Recent research conducted in Lake Tahoe, USA found that UVC light causes damage to plant DNA and cellular structure, causing them to die. Research is continuing to investigate effects of exposure times, and distance from the lake bottom. Monitoring has found that UVC does not affect dissolved oxygen, pH, temperature or turbidity. New research is also underway to investigate if this technology has any impacts on the microorganisms in the lake sediment and how it can be up-scaled (Cudahy 2017).

Laminar flow aeration technology

Laminar flow aeration injects oxygen into the lake bed increasing aerobic decomposition of organic material in the sediments and water column. This reduces organic material and nutrients and research has shown that aeration can reduce the growth of Eurasian water milfoil by 20% (Cooley *et al.* 1980). Currently research is underway to investigate the effects of laminar flow aeration on invasive aquatic plants in Lake Tahoe (TRC 2019).

2.3.3 Chemical control

As previously mentioned, chemical control in the form of commercial herbicides was a successful method for controlling *L. major* in Lough Corrib. Herbicides, however, are no longer an option as the only herbicide approved for aquatic use in Ireland is glyphosate in the form of Roundup Bioactive (J. Caffrey pers. comm.), which is not appropriate for *L. major* control.

Salt and acetic acid are examples of non-commercial natural herbicides that have been tested in the control of invasive plants. Salt is not used in freshwater habitats probably due to its non-selective toxicity (Hussner *et al.* 2017). Tapioca starch pearls saturated with acetic acid and placed beneath a non-porous benthic barrier have been successfully used to control *Potamogeton crispus* (Curlyleaf pondweed) in California, USA. Tapioca starch pearls facilitate the slow release of acetic acid and significantly reduce turion sprouting (Barr and Ditomaso 2014).

2.3.4 Biological control

Biological control is the introduction by humans of a parasite, predator or pathogen into an environment for the control of a target plant or animal pest (Davidson 2015). Biological control can reduce or remove the need for expensive control and eradication operations by maintaining the invasion at acceptable levels (Baars 2012). Indeed, it has been argued that biological control offers the only safe, economic, and environmentally sustainable solution (McFadyen 1998). Unfortunately the release of non-native organisms for biological control is usually considered risky and fails to find popular support (Simberloff and Stiling 1996). This is probably due to a small proportion of bio-control introductions that have had severe negative unforeseen effects in the past, e.g. the Harlequin ladybird in Europe and the USA. However, since strict quarantine screening and risk/benefit analysis were introduced, there has been a decrease in undesired non-target effects (Messing and Wright 2006). Research suggests that 0.5% of 400 insect, mite, and fungal species used in classical weed biological control world-wide have resulted in significant damage to non-target organisms. These impacts were probably predictable from host range testing and likely preventable (Fowler *et al.* 2000). In addition, it was found that 83% of biological control programmes for environmental weeds in New Zealand were fully or a partially successful (Fowler *et al.* 2000).

Current evidence indicates that biological control could provide a safe and cost effective control method, particularly as *L. major* has no close relatives native to Europe (Baars *et al.* 2010). There is now a considerable body of research on insect species that appear to be suitable biological control agents (Baars *et al.* 2010). To date, biological control research has focused on the leaf mining fly *Hydrellia lagarosiphon,* as it has been identified as host-specific. Pre-release trials indicate that 3-4 larvae per shoot tip can contribute to the suppression of plant growth, with negative effects on shoot tip length and biomass

(Mangan and Baars 2016). Investigations into its biology indicate that permanent populations could likely establish across most of Europe (Mangan and Baars 2013). Research on a chironomid midge, *Polypedilum* n. sp. found that the larvae feed on the main and side shoots of *L. major*, stunting its growth (Earle *et al.* 2013). However, rigorous host specificity testing is required to evaluate any undesired non-target effects (Earle *et al.* 2013).

2.4 Prevention

Preventing the spread of IAS to both new waterbodies or to new sites in already invaded waterbodies, requires a multifaceted approach. Biological invasions are a product of human activity, therefore prevention must consider human activities and behaviours (Tollington *et al.* 2017). Raising public awareness and empowering people to take preventative measures are fundamental pillars to prevent IAS spread.

2.4.1 Education and outreach

Successful campaigns use a range of different communication mediums and typically include signage, website content, classroom, public meetings and active engagement of the public in activities. Stakeholder biosecurity campaigns such as “*Check, Clean, Dry*” aim to reduce aquatic invasive species spread by creating awareness and endorsing best practice (Anderson *et al.* 2015). Current signage is mainly limited to launch sites on Lough Corrib. A novel idea that may augment this is placing signage along waterways, particularly in bays where the aquatic plant is difficulty to treat (e.g. Drumsnauv Bay and the western arm), or busy parts of the lake, notifying and reminding people to check and clean their equipment when moving from one area to another.

2.4.2 Disinfection

Disinfection refers to actions ensuring that invasive species are not transferred from one site to another. Equipment such as angling gear, footwear, outboards and kayaks are known vectors for aquatic invasive species (Davis and Darling 2017). Hence, a proven disinfection method is required when moving equipment between infected and non-infected areas. In Lake Tahoe, boat back-up stations allow boat users to clean their boats before moving to other areas within the lake. Off the water, immersion of equipment in disinfectants such as Virkon Aquatic® and Virasure ® has shown variable results and should not be considered completely effective against *L. major* (Crane *et al*. 2019; Cuthbert *et al.* 2018). Applying steam for 30 seconds appears to be an effective treatment (Coughlan *et al.* 2020; Crane *et al.* 2019). In practice ensuring equipment is free of *L. major* fragments and disposing of it in an appropriate manner is likely the most effective method to prevent its spread.

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

3.1 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 methods can be time and resource intensive. Several innovative solutions are now available, including electronic data collection applications and remote sensing technologies such as; multispectral UAV (Unmanned Aerial Vehicle i.e. drone) and satellite imagery, hydroacoustics and machine learning algorithms (Cariveau *et al.* 2019; Jones *et al.* 2018; Stocks *et al.* 2019; Whyte *et al.* 2018; Zhou *et al.* 2018). The aims of this work package are to trial a suite of new technologies and develop a modern integrated survey approach for assessing *L. major* in Lough Corrib.

3.1.1 Traditional sampling methods

Previous research projects on Lough Corrib (2005 and 2013) typically surveyed the plant using direct observations, bathyscopes and snorkel-towing along pre-determined transect lines, marking infestations with handheld GPS units. These approaches provided point and line data but were time consuming, enabling only a small proportion of the lake to be surveyed annually (Millane *et al.* 2013) and carried an element of health and safety risk. Since 2013, most *L. major* surveys have been conducted by the contracted control team using visual observations generally in known problem areas, or where recent sightings have been reported. This allows the team to simultaneously assess the infestation and site parameters. A disadvantage of this targeted approach, however, is that large areas of the lake remain un-surveyed. Furthermore, sampling is not quantitative and requires return visits for up-to-date assessment.

3.1.2 New sampling methods - remote sensing

Remote sensing involves determining the physical characteristics of an area without making actual contact with the objects therein. Ground-truth sampling, however, is normally required to validate the results. The choice of remote sensing technique typically depends on the underlying question and method limitations. Underwater imagery (Yoklavich *et al.* 2015), hydroacoustics (e.g. Winfield *et al.* 2007) and multispectral imagery, both aerial and satellite (e.g. Free *et al.* 2020) are appropriate remote sensing techniques for sampling aquatic plants.

Underwater imagery

High definition underwater imagery and powerful lighting are becoming increasingly affordable. Consequently, underwater imagery is now commonly used to assess benthic habitat, species and communities (Yoklavich *et al.* 2015). Cameras can be deployed using remotely operated vehicles (ROV's), attached to a towing body, or in shallow areas they can be directly attached to a boat.

Hydroacoustics

Hydroacoustics uses sound to map the underwater landscape and can identify, with a relative degree of certainty, plants that vary greatly in height (Bučas *et al.* 2016). Given the tall and dendritic character of *L. major,* it is likely that it will be identifiable in hydroacoustic echograms. Therefore hydroacoustics has the potential to provide a rapid early detection method while the plant is below the surface and difficult to detect. Hydroacoustic surveys can also provide additional information, including colonisation depth, slope and substrate type (Godlewska *et al.* 2004; Winfield *et al.* 2007).

Multispectral imagery (UAV and satellites)

Multispectral cameras measure light in spectral bands and different surfaces can be identified as they reflect and absorb light differently. In the case of vegetation, green leaves are highly reflective of near-infrared radiation (NIR). Multispectral cameras and resultant images offer several different bandwidths which provide enough signature variation to classify vegetation, identify species and track changes over time. Multispectral imagery is therefore effective for mapping submergent aquatic vegetation at large and small spatial scales (Xie *et al.* 2008; Zhou *et al.* 2018), particularly in clear, shallow lakes (Hunter *et al.* 2010). Multispectral cameras can be deployed by satellite, unmanned aerial vehicles (UAV's) and aeroplanes. The deployment mode is usually determined by the size of the area being surveyed, the spatial and spectral resolution requirements and cost. The European Space Agency's, Copernicus, Sentinel-2 satellite data can, depending on cloud and glare, map vegetation across an entire lake the size of Lough Corrib (18,240 ha) at a 10 m/pixel resolution every 5 days. In contrast, UAV's with their higher spatial resolution (>0.1 m/pixel), are better suited to detailed mapping of small near-shore areas. However, multispectral imagery can be affected by poor water clarity, plant depth, glare and water surface roughness (Bernardo *et al.* 2018; Mobley 2015; Yadav *et al.* 2017). Hence, this method is often used alongside other methods unaffected by these issues, such as hydroacoustics.

3.1.3 Electronic data collection and management system

Recent developments in digital field data collection have improved the efficacy of surveys that inform management, with a host of new field data applications becoming available (e.g. ArcGIS Apps, Fulcrum) (Cariveau *et al.* 2019). Current and historical distribution datasets related to *L. major* in Lough Corrib are contained in a number of disparate databases, in a variety of formats that impede their compatibility and use.

3.1.4 Aims of the work package

This work package aims to test the effectiveness of various remote sensing methods for mapping *L. major* in Lough Corrib and introduce a data management and electronic data collection system.

3.2 Materials & methods

3.2.1 Study area and sampling period

A number of locations where *L. major* is known to occur were surveyed using a range of sampling methods between December 2018 and October 2019 (Figure 3.1). The results of UAV and satellite studies at Drumsnauv Bay (Table 3.1) and hydroacoustic surveys at Annaghdown Bay, Lackavrea and Carrowgariff are reported here. *L. major* was harvested at Drumsnauv during the study (see chapter 6). Stationary underwater imagery was trialled across 200 locations throughout the lake while mobile underwater imagery was tested in the Cong area and ROV imagery was assessed in Drumsnauv Bay.

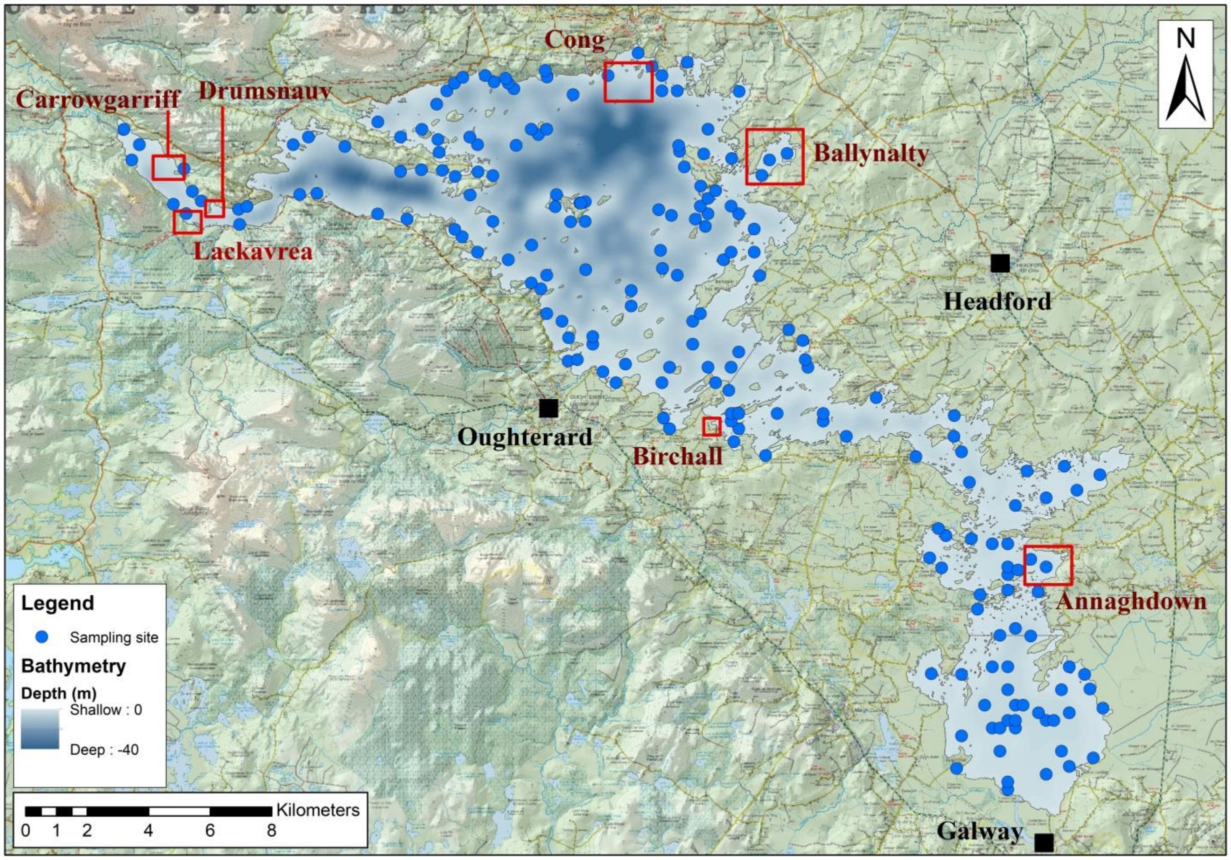

Figure 3.1. Method testing areas (red) on Lough Corrib, 2018 and 2019.

Table 3.1. UAV, satellite imagery and direct visual observations (DVO) from boat surveys of Drumsnauv Bay

Survey	Date	Method	RGB	NGB
Pre-cutting (8-months)	28/10/2018	Satellite	-	x
Pre-cutting	29/05/2019	DVO Boat	-	-
Pre-cutting	05/06/2019	UAV	x	x
During cutting	10/06/2019	Satellite	-	x
Post-cutting (2-months)	16/08/2019	UAV	-	x
Post-cutting (3-months)	18/09/2019	Satellite	-	x
Post-cutting (3.5-months)	02/10/2019	UAV	x	x

Note: Cutting/harvesting trial undertaken between the 5th and 20th of June 2019.

3.2.2 Mapping and quantifying *L. major* using underwater photography and videography

A drop camera and three waterproof cameras (HD-fisheye lens and two HD-regular lenses) were tested for use in *L. major* mapping, other macrophyte mapping and substrate assessments. The cameras were tested under mobile (transect) and stationary (site) scenarios at various locations around the lake (depth 0 to12 m). Cameras were evaluated based on image quality, ease of use and concordance with traditional grapnel and grab sampling. A Remotely Operated Vehicle (ROV) with a high definition 4K camera and LED lights was used to view and record imagery underwater in Drumsnauv Bay.

3.2.3 Mapping *L. major* using hydroacoustics

Vertical beam hydroacoustic surveys were carried out in Annaghdown Bay (28th February to 1st of March 2019) and Carrowgarriff and Lackavrea (20th & 27th August 2019) using a systematic parallel transect design (Figure 3.2). Acoustic detections were ground-truthed using sediment grabs (Figure 3.2).

Hydroacoustic data was recorded using a scientific echosounder. Maximum macrophyte height and lake depth were then exported and interpolated using inverse distance weighting (IDW) to generate probable *L. major* distribution and bathymetric maps of the sampled areas.

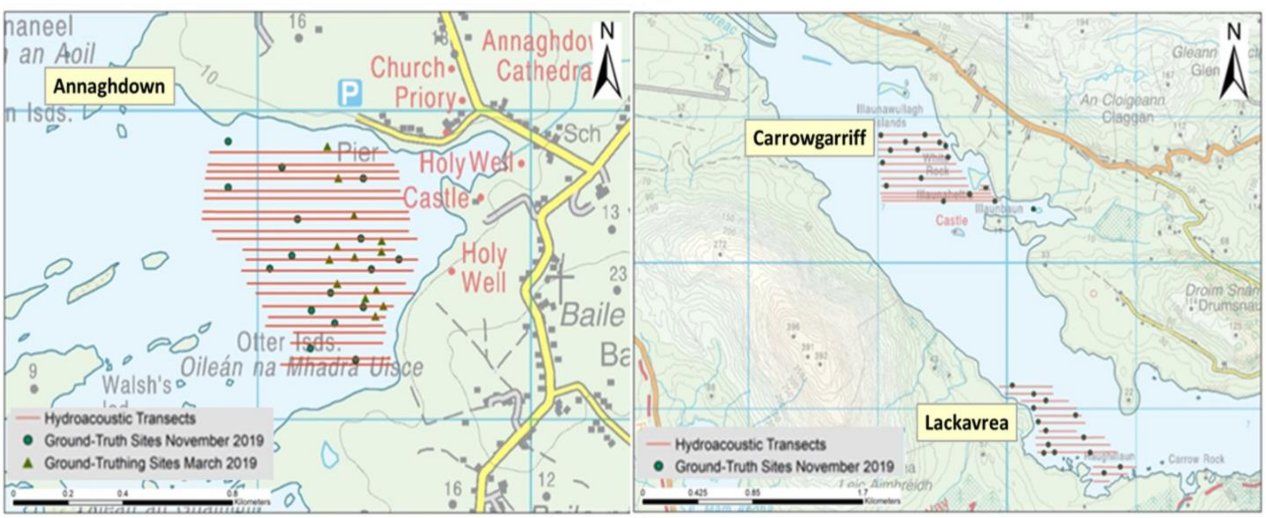

Figure 3.2. Hydroacoustic transects and ground-truth sampling sites

3.2.4 Mapping *L. major* using UAV and satellite imagery

Two different UAV models were used to capture images from an altitude of 50 m on Lough Corrib. RGB images were captured with the UAV's in-built camera. The near-infrared-Green-Blue (NGB) images were captured with an externally mounted NGB camera. For one UAV model the mount orientated the camera vertically, but on the other UAV the mount was tilted slightly from vertical. NGB images were radiometrically calibrated using a reflectance calibration ground target. The UAV's were operated using both an android phone and tablet and automated and manual flights were flown. The impact of these differences was appraised. Orthomosaic images were generated using Drone2Map for ArcGIS.

Sentinel-2 satellite images were downloaded for available cloud free dates using the European Space Agency's (ESA) Copernicus Open Access Hub (https://scihub.copernicus.eu/). Images were ground-truthed using the June RGB orthomosaic.

L. major ground-truthing was mapped by manually tracing the outline of observed *L. major* patches in the RGB orthomosaic. For multispectral imagery, mapping was conducted by generating Normalized Difference Aquatic Vegetation Index (NDAVI) raster layers in ArcGIS 10.5. The NDAVI is commonly used to identify aquatic vegetation. It is based on the amount of blue and near-infrared (NIR) light, reflected by a surface (Villa *et al.* 2014, 2013). Vegetation was categorised into *Dense* and *Sparse* based on NDAVI values derived from UAV and Sentinel-2 images and ground-truth observations from the RGB orthomosaics (Table 3.2). Polygons representing *L. major* monocultures and mixed stands (*L. major* and emergent vegetation) were also created using this RGB orthomosaic. UAV, satellite and visual ground-truth data estimates for the area, perimeter and NDAVI were estimated for a number of sampling occasions.

Table 3.2. NDAVI values for vegetation map classification

Map classification	Satellite NDAVI value range	UAV NDAVI value range
Dense vegetation	-0.09 - +0.35	+0.16 - +1.00
Sparse vegetation	-0.36 - -0.09	+0.05 - +0.16
No vegetation	-0.66 - -0.36	-0.59 - +0.05

3.2.5 Ground-truth Sampling Techniques

Ground-truth sampling techniques were used to verify *L. major* distribution detected by hydroacoustics and multispectral imagery. Where the plant was at the surface, two visual methods were tested, 1) direct visual observations (DVO) from a boat, and 2) inspection of RGB orthomosaics. Where the aquatic plant was beneath the surface grapnel hooks, grabs, a bathyscope and underwater imagery were used.

3.2.6 GIS based electronic data collection applications

An off-the-shelf GIS based electronic data collection application was used to collect and manage point data during surveys, control operations and incidental sightings (see example in Appendix 9.1). A similar off-the-shelf application with additional functionality was used to gather data on *L. major* distribution as polygons, lines and points. To optimise GPS accuracy (≤3 m), GIS applications were paired via Bluetooth to a handheld GPS.

3.3 Results

3.3.1 Mapping and quantifying *L. major* distribution using underwater imagery

Waterproof cameras

Natural light decreased with depth and this affected the quality of underwater imagery. Waterproof lighting addressed this issue for stationary photos but provided mixed results for mobile sampling due to the changing depth of the lake bed. Consequently, mobile sampling was only successful in areas shallower than 4 m where Secchi disc measurements were >6 m. The HD camera with fish eye lens provided the best images when in video mode, but the absence of a live feed facility prevented on site image quality assessment (Plate 3.1). The non-HD live feed drop camera allowed image quality assessment in real-time, but provided lower resolution images, making plant and substrate identification difficult.

The main advantages of using waterproof cameras were the clarity with which the underwater landscape could be viewed and ease of use. At relatively deep sites quantitative surveys were carried out without the need for divers. At shallow sites the HD camera performed better than the bathyscope eliminating glare and reducing the effects of poor water clarity. Issues with lighting and image quality can be addressed in the future to improve the performance of waterproof cameras for mobile sampling.

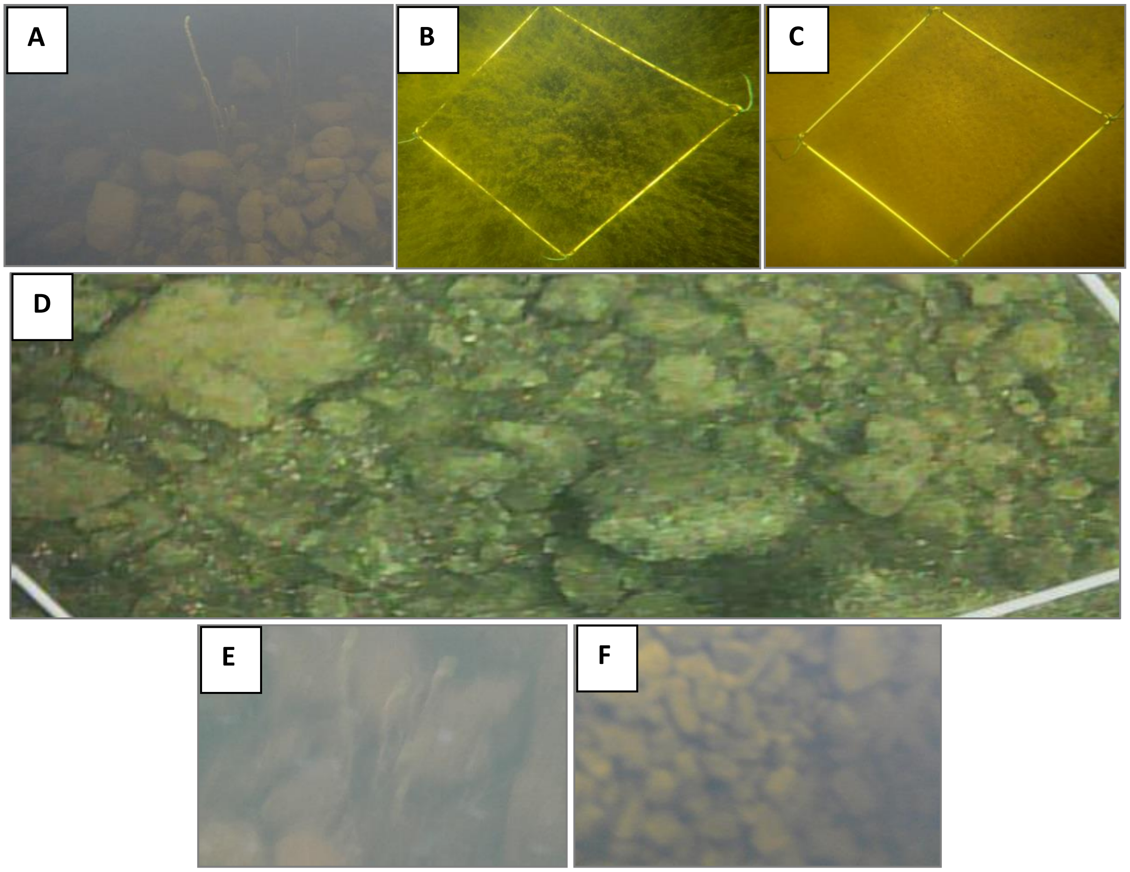

Plate 3.1 Image quality comparison; (A, B & C) HD-fish eye lens camera (video still-images), (D) Non-HD drop camera (video still-image) and (E & F) Non-HD camera images.

Remotely Operated Vehicle (ROV)

The high definition images from the ROV were sufficient to identify plants, substrate and fish fry in the sampled area (Plate 3.2). The main advantage of the ROV was its ability to provide high resolution visual observations without the need for divers or office time to review imagery. A disadvantage of the ROV tested was that it was not possible to collect the precise GPS location of the plants and substrate observed. Instead, plants and substrate were assigned to the delineated areas sampled.

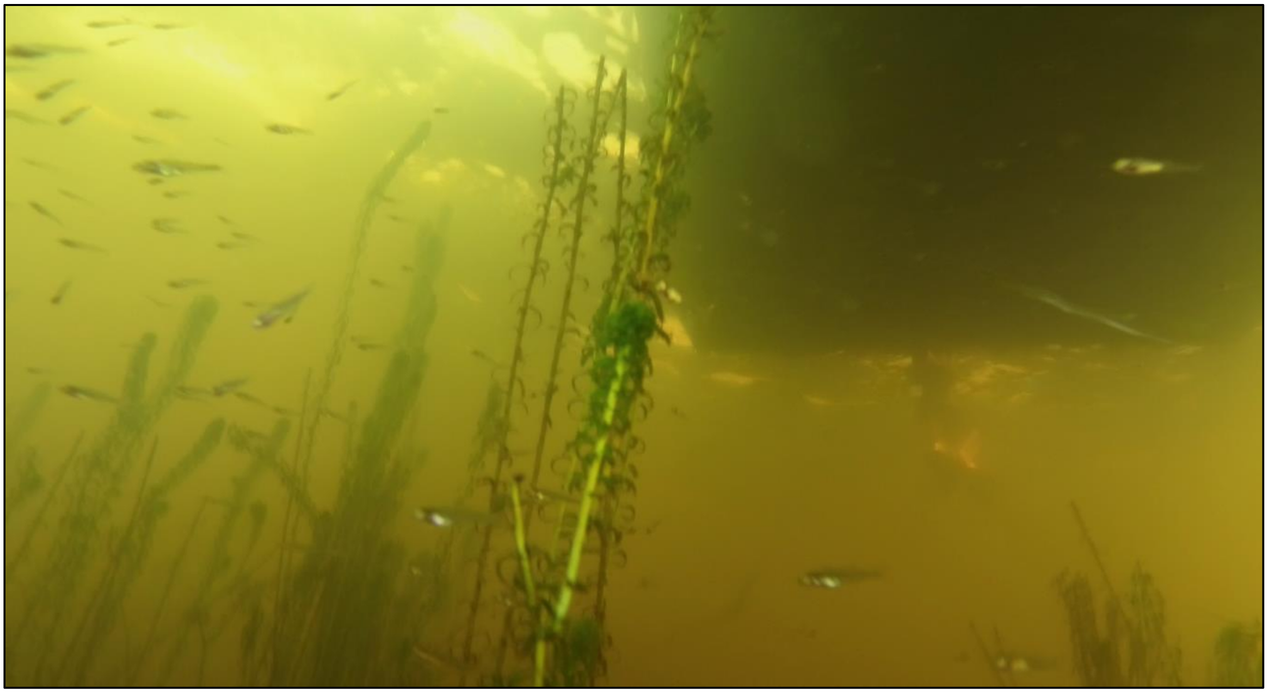

Plate 3.2 Juvenile coarse fish among *L. major,* acquired using an ROV with HD camera.

3.3.2 Mapping *L. major* using hydroacoustics

There was a clear association between acoustic maximum vegetation height and ground-truth *L. major* presence/absence across the study areas (Annaghdown, Carrowgarrif and Lackavrea) (Figure 3.3). *L. major* was, therefore, considered present when vegetation height was >1.0 m. Hydroacoustics were only useful where *L. major* occurred ≥0.4 m below the water's surface, due to propeller depth and fragmentation risk. One clear advantage of this type of sampling was that it was efficient, taking an average of two days at each location. A disadvantage was that image processing took a considerable length of time due to the need to trace the intricate nature of *L. major* echoes (Plate 3.3). Hydroacoustics also provided useful high resolution mapping of habitat (depth of colonisation, slope and substrate type). Bathymetric models showed *L. major to* grow at different depths in each bay (1 to 3m in Lackavrea, 2 to 3m in Carrowgarriff and >4m in Annaghdown) (Figure 3.3).

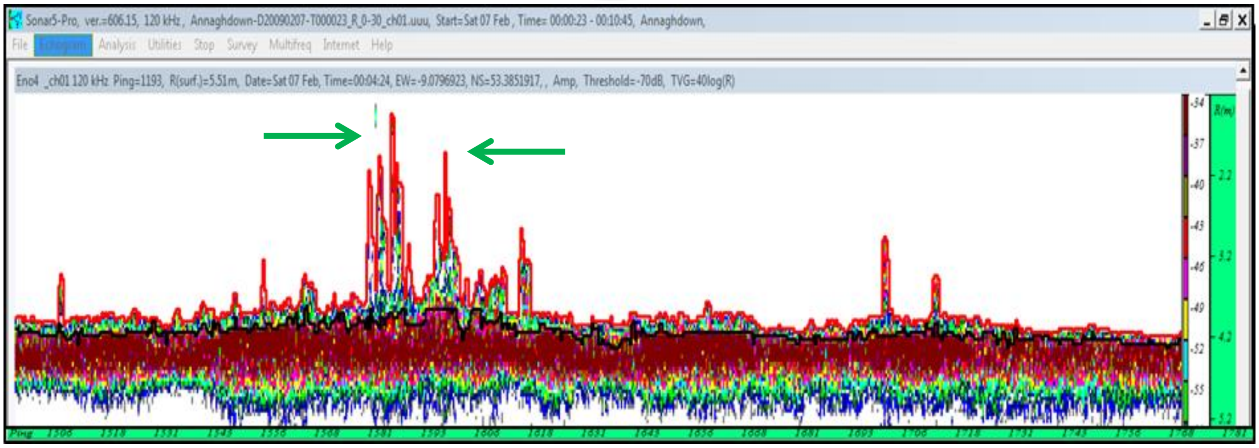

Plate 3.3. Hydroacoustic echogram showing *L. major*.

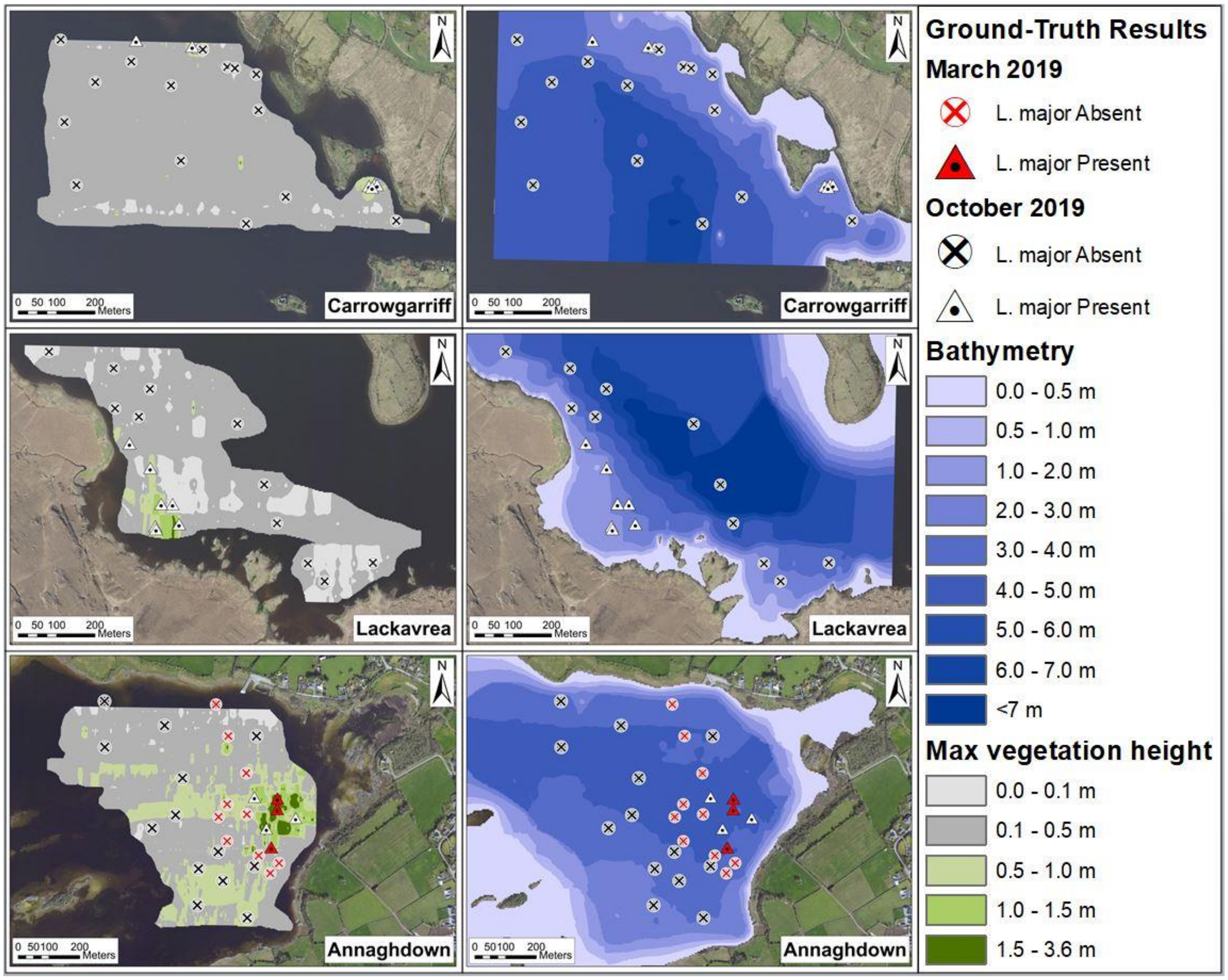

Figure 3.3. Interpolated maximum vegetation height recorded, including ground-truth results.

3.3.3 Mapping *L. major* using UAV and satellite imagery

Where *L. major* occurred at the surface, it was possible to determine patch area, perimeter and vegetative density by manually tracing areas from RGB orthomosaics or by automatically calculating NDAVI using multispectral UAV and satellite imagery.

UAV Image Acquisition

The android tablet performed better than the phone, completing UAV missions with fewer operational problems. Due to re-current issues with automated flight path software, manual flights were also undertaken, but manual flights were less efficient with inferior results due to inadequate image overlap. The image quality from the externally mounted NGB camera differed between both UAV's. The UAV with a tilted NGB camera mount provided inferior images to that of the UAV with the horizontal mount.

Orthomosaic Generation

Orthomosaic stitching was dependent on image quality, glare, camera and process settings (Figure 3.4). Geo-calibration struggled in open water areas due to a lack of identifiable features on the surface, as well as glare and camera vibration (Figure 3.4).

For RGB images, the camera was integrated into the UAV software and mounted on a stabilising gimbal. Consequently the RGB images were in-focus and it was possible to improve image geo-calibration by incorporating the automatic flight plan (Figure 3.5). Hence the RGB imagery supplied more complete coverage of the open water area than the NGB.

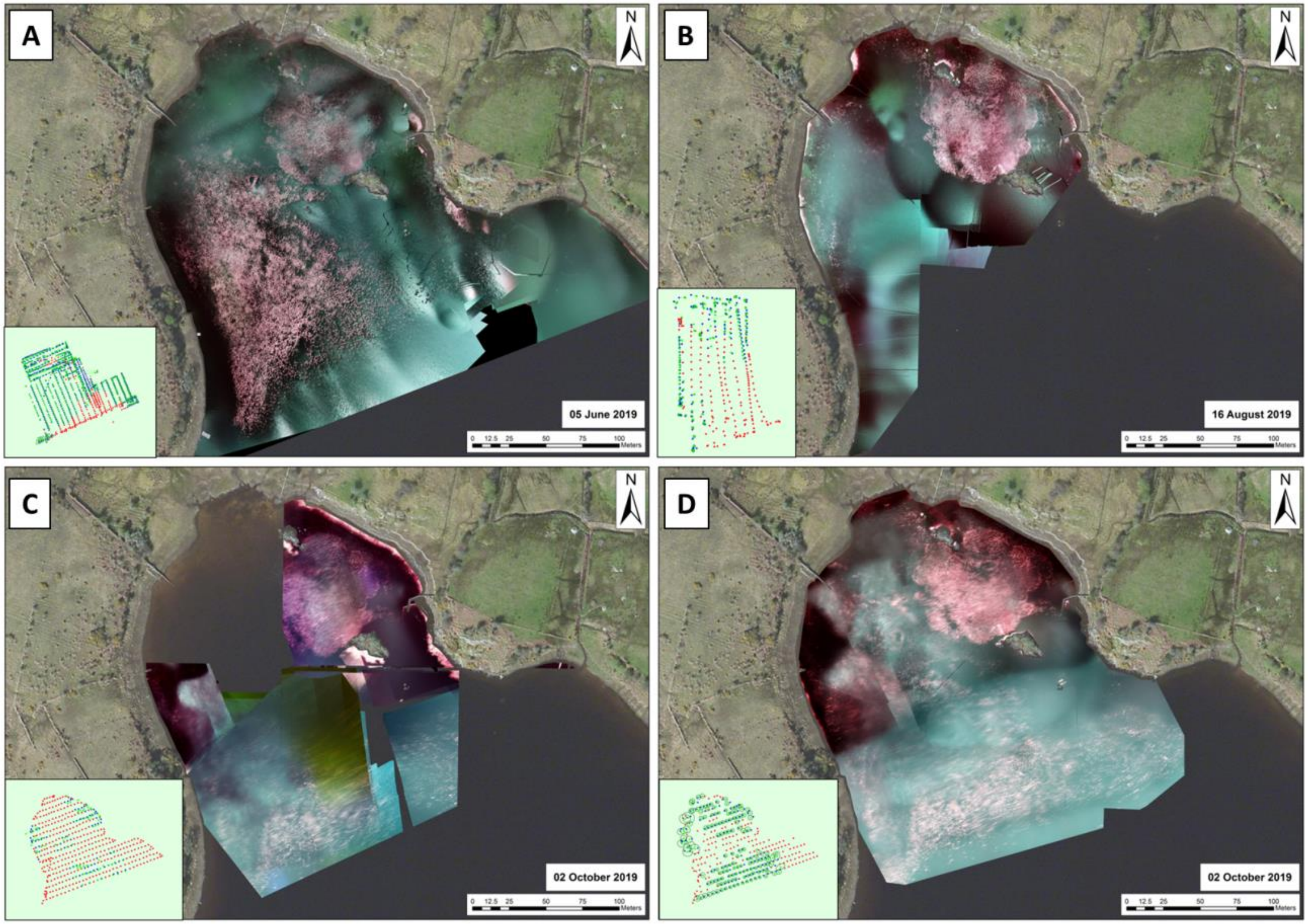

Figure 3.4. Drumsnauv Bay NGB orthomosaic created from a UAV flight (A: 5th June 2019, B: 16th August 2019, C: 2nd October 2019 and D: not radiometrically calibrated 2nd October 2019). Insert shows the orthomosaic image position. Offset between initial (blue dots) and computed (green dots) image positions. Red dots indicate disabled images which are not included in the final orthomosaic due to geo-calibration failure. Dark green ellipses indicate the absolute position uncertainty of the bundle block adjustment result (Images from Drone2Map Report).

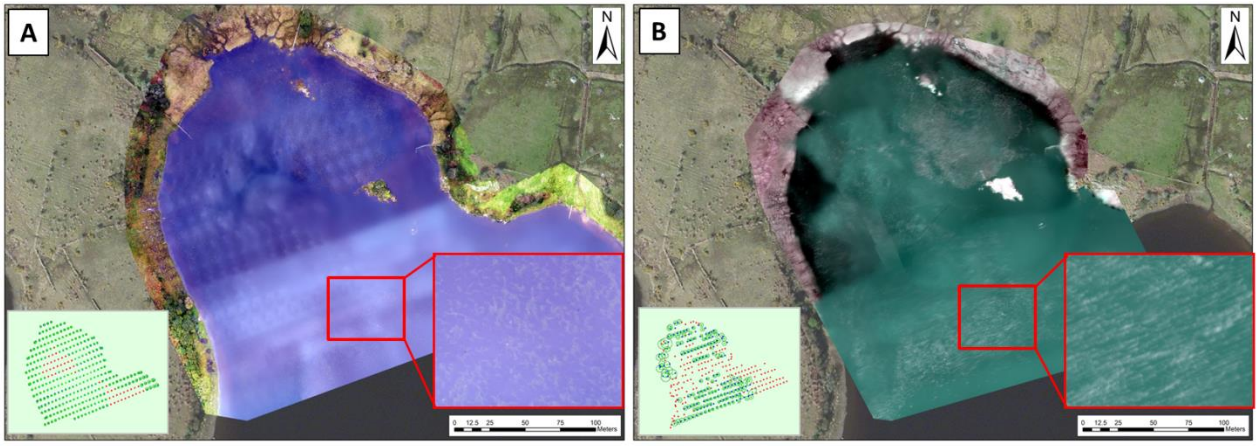

Figure 3.5. Orthomosaics of Drumsnauv Bay from UAV flights (A) in-built RBG camera and (B) externally mounted NGB camera

Mapping and quantifying *L. major* using UAV and satellite imagery

Vegetation was clearly visible in Drumsnauv Bay using the multispectral satellite and UAV imagery due to its high reflectance of infra-red light (Plate 3.4). However, it was not possible to identify *L. major* and differentiate vegetation types using NGB images due to inferior image resolution and quality and the unnatural colouration. In contrast *L. major* was clearly identifiable using the RGB imagery (Plate 3.4); however, this was time consuming (Figure 3.6A and B and Table 3.3).

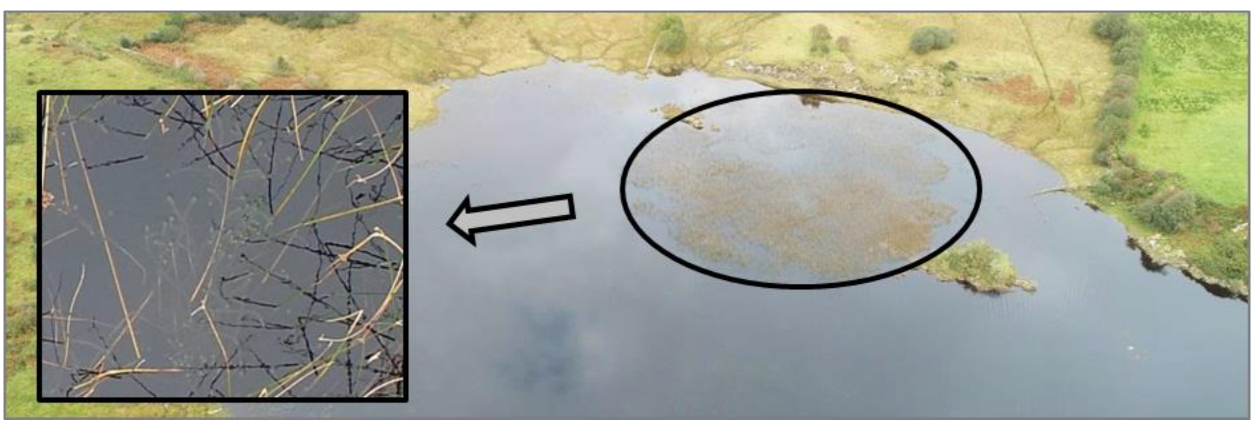

Plate 3.4. Stands of emergent vegetation infested with patches of *L. major* circled in black in Drumsnauv Bay (Insert: submerged *L. major*).

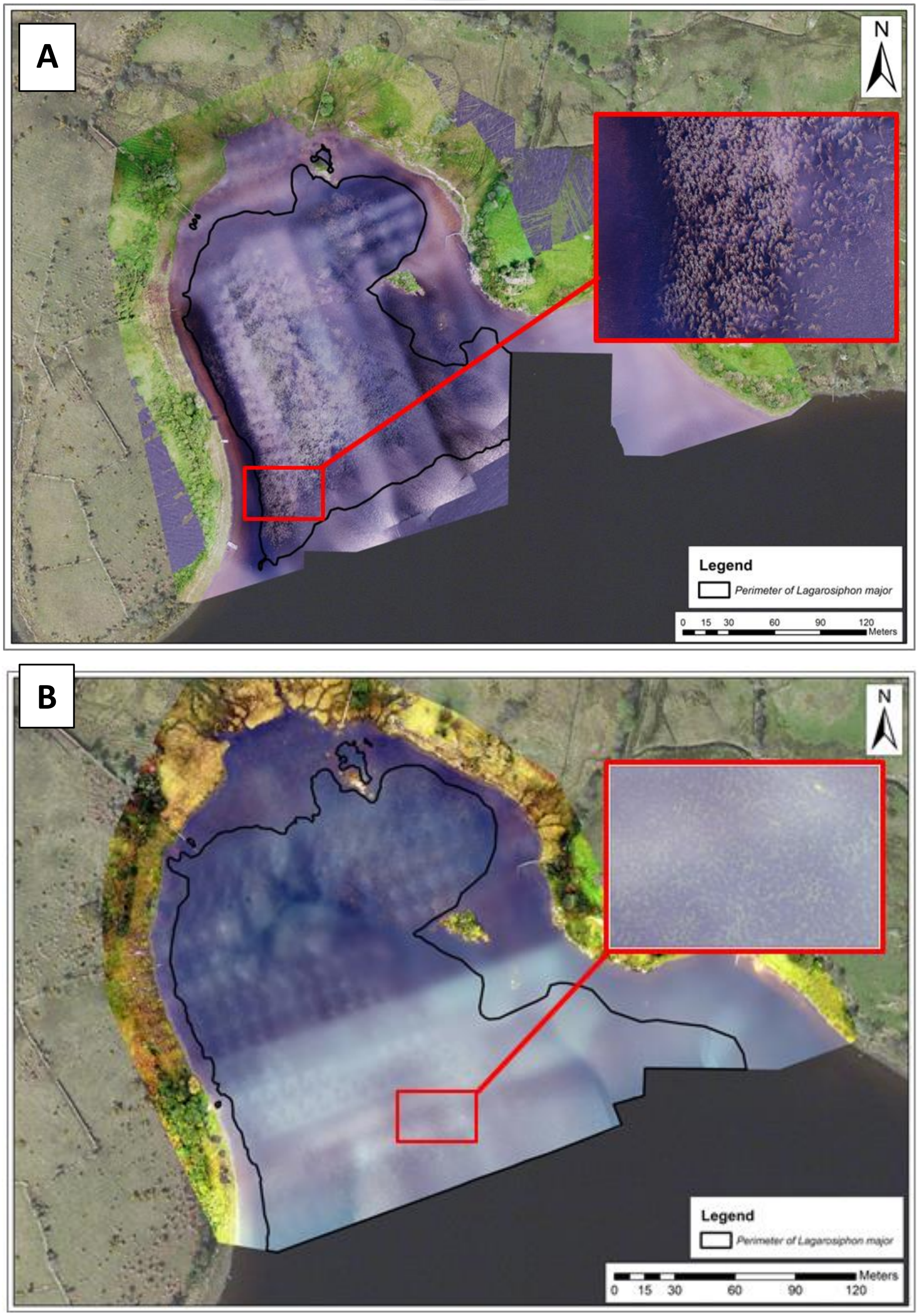

Figure 3.6. RGB Orthomosaics of Drumsnauv Bay captured on (A) the 5th of June 2019 and (B) the 2nd of October 2019.

Table 3.3. Area, perimeter and NDAVI of *L. major* from direct visual observations (DVO) by boat, UAV (RGB & NGB) and Sentinel-2 images (before, during and after an aquatic weed harvester trial on Drumsnauv Bay).

Acquisition method	Survey date	Ground pixel size (cm)	Mean NDAVI	Min NDAVI	Max NDAVI	Area of *L. major* (m^2)	Perimeter of *L. major* (m)
Pre-Cutting							
DVO by boat	29/05/2019	-	-	-	-	25,659	745
UAV (RGB)	05/06/2019	2.13	-	-	-	30,981	1,027
UAV (NGB)	05/06/2019	2.15	+0.10	-0.52	+0.41	29,983	1,133
During-Cutting							
Sentinel-2	10/06/2019	1,000	-0.26	-0.56	+0.19	*19,747	*986
Post-cutting							
Sentinel-2	18/09/2019	1,000	-0.37	-0.49	+0.33	10,078	1,157
UAV (RGB)	02/10/2019	2.42	-	-	-	34,119	1,138

Aquatic weed harvester trial had commenced

Multispectral UAV and satellite imagery facilitated the rapid detection of aquatic vegetation and provided quantitative vegetation density estimates (Figure 3.7 & Table 3.3). Direct temporal comparisons of the multispectral UAV and satellite imagery were not possible as cloud free satellite images did not coincide with the UAV sampling dates (Table 3.3). Satellite imagery recorded a decrease in *L. major,* post-cutting, and patchy canopy re-establishment two months later (Table 3.3). This pattern was also apparent in the incomplete multispectral UAV orthomosaic (Figure 3.7). Similar patterns in the *Dense* and *Sparse* vegetation were apparent in June (Figure 3.7A and B) and later in August and September (Figure 3.7C and D). Some areas erroneously received a high NDAVI value (Figure 3.7A and C (circled in red)). Comparison of the *L. major* perimeter derived from the RGB orthomosaic and NDAVI results highlight that NDAVI is informative but requires robust ground-truth data (Figure 3.8).

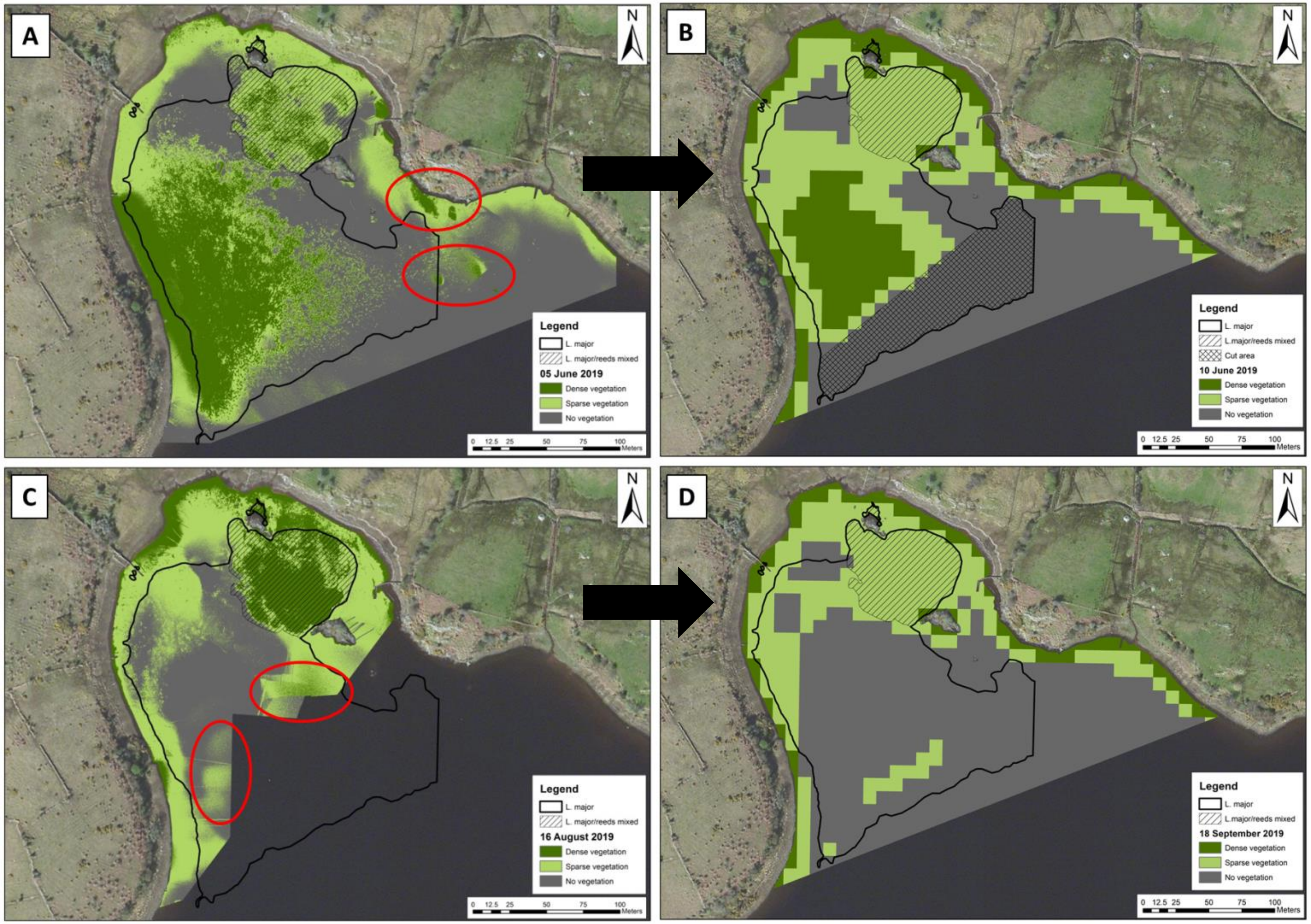

Figure 3.7. NDAVI showing *Dense* and *Sparse* vegetation using UAV (A & C) and Sentinel-2 (B & D) acquired images. Image acquisition dates were: A. 05 June 2019 B. 10 June 2019 C. 16 August 2019 D. 18 September 2019. Red circled areas represent orthomosaic stitching errors and therefore do not represent valid NDAVI values.

Ground-truth Data

RGB orthomosaics provided highly accurate ground-truth data (Figure 3.8 and Table 3.3) for the multispectral imagery due to the UAV's high resolution images and its ability to sample the entire bay (Plate 3.4 and Figure 3.6). Visual observations from boats were deemed subjective and provided incomplete coverage, due to the navigational issues sampling in shallow waters (Figure 3.8). Hence, estimates from direct visual observations (boat) did not include *L. major* present in the stands of emergent vegetation beds (Table 3.3).

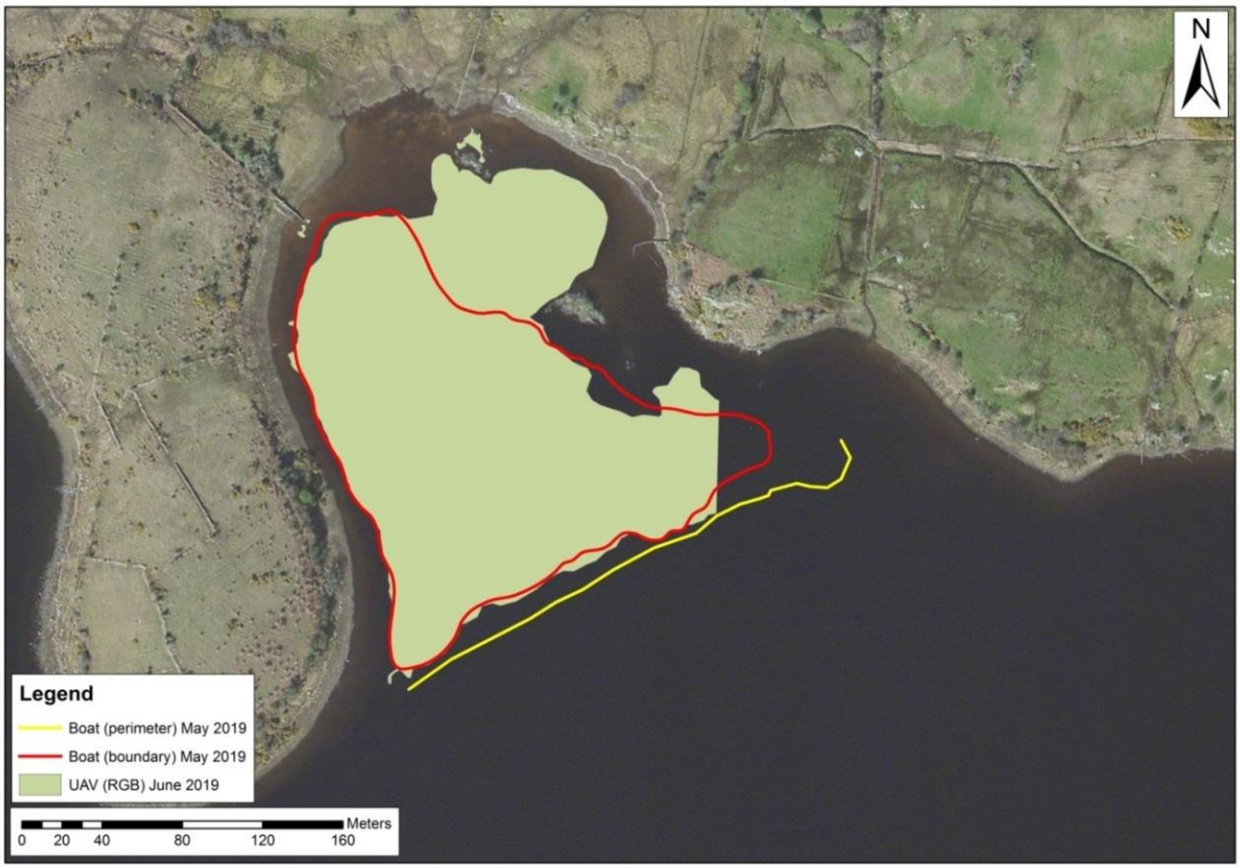

Figure 3.8. Ground-truth sampling.

3.3.4 <u>GIS based electronic data collection applications</u>

The point only electronic data collection application was easy to use and the absence of paper significantly improved productivity. Furthermore, the ability to apply constraints to the data fields ensured that input errors were rare. The ability to instantly analyse spatial patterns, check for outliers (Plate 3.5) and edit errors within the data collection app was also a benefit. Maps were generated in a few quick steps as the data is recorded instantaneously within GIS software, which may be reviewed at the time of collection. From a health and safety point of view, office based staff could unobtrusively obtain position updates on the survey team more frequently than by radio communications alone.

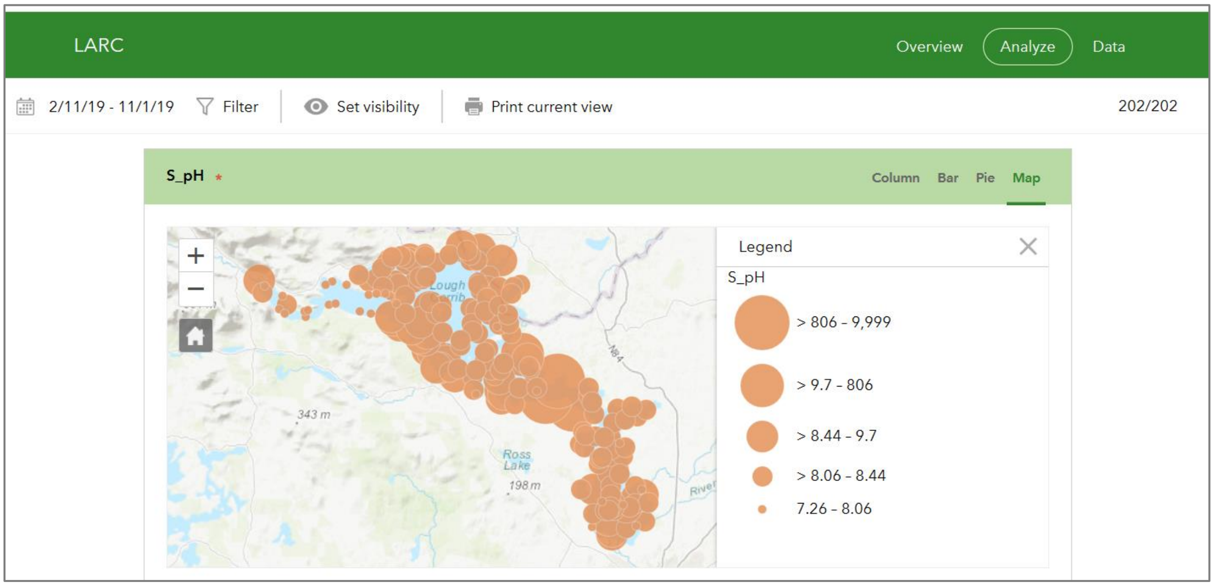

Plate 3.5. LARC electronic survey form, showing spatial patterns in surface pH, (errors quickly detectable (e.g. pH > 9.7)

The electronic data collection application with additional features such as polygons and lines was also easy to use, with rapid collection of geo-referenced ground-truth data. This method saved time in the office, as the data collected was already compatible with GIS and required minimal processing. In addition, it was possible to use the application offline in areas with limited internet coverage.

3.4 Discussion

The morphology of *L. major* (*collapsed* or *erect*), environmental conditions (e.g. weather, water clarity) and spatial resolution requirements are key considerations when choosing which methods to apply for surveying in Lough Corrib. Results collected to date indicate that an integrated multi-method sampling approach, combining underwater imagery with hydroacoustics, UAV's (aerial drones) and multispectral satellite imagery, is required to provide comprehensive distribution maps of *L. major* in Lough Corrib.

Underwater imagery was found to be a highly effective tool for quantitatively sampling aquatic plants and substrate, the choice of camera and light source were important. Of the cameras trialled, the HD camera with fish-eye lens produced the best quality images across the depth range sampled (1 to 12 m) when used in video mode with underwater lights. The absence of a live feed facility, however, meant that it was not possible to verify image quality and the presence of *L. major* in real-time, resulting in the need to revisit some sites. This was a disadvantage of the set up deployed during this study; however, these issues can be addressed by using a high-resolution camera with both a live-fed and geo-referencing ability. Such a solution is recommended as it will provide more accurate sampling of submerged plants and substrates, larger than gravel than traditional methods (e.g. bathyscopes, grab) and automatically geo-reference and timestamp the data.

Hydroacoustics was suited to sampling submerged stands of *L. major* and its habitat, rapidly collecting high resolution data. Ground-truth sampling revealed that vegetation height was a good indicator of *L. major* presence, with vegetation >1 m tall, most likely *L. major.* Although hydroacoustics can be impeded by weather the main disadvantage of using hydroacoustics here was the amount of time spent post-processing. Accordingly, the scientific hydroacoustic equipment used in this study appears better suited to small-scale scientific studies, rather than broad-scale mapping. Vegetation height >1 m, typical of *L. major* is easily obtained from modern low cost non-scientific fish finders which can operate at higher speeds and automatically generate detailed maps with little expert knowledge required (e.g Helminen *et al.* 2019). Nevertheless, there would still be a need to ground-truth the data, returning to sites with taller vegetation (>1 m) to ensure accurate species identification. Finally it is recommended that care be taken to avoid areas where *L. major* is close to the surface (≤0.4 m) to avoid fragmentation.

UAV's were extremely useful for mapping small near-shore weeded areas. In these areas images taken by UAV's had several advantages in comparison to high-resolution (40 cm pixel) satellite imagery (e.g. Worldview 4) and direct visual observations from boats. In comparison to high-resolution satellite imagery UAV's offer low cost, rapid, high-resolution multispectral imagery and RGB ground-truth mapping option. Relative to direct visual observations from boats; UAV's yielded better observational data in areas that were highly weeded and difficult to navigate with a boat. However, in calm weather direct visual observations successfully mapped submerged *L. major* that was invisible in UAV and satellite imagery. The main disadvantages of using UAV's in this study were the requirement for calm, dry, overcast weather conditions and the 300 m distance from operator flight limit. UAV technology is constantly improving and some of these issues are currently diminishing as new models that operate in rain and higher winds are now coming to market.

Multispectral imagery provided accurate distribution maps and quantitative data on *L. major* where it occurred at the surface. Despite differences in resolution, imagery from UAV's and satellites provided similar spatial distribution and perimeter estimates. NDAVI values recorded using both technologies in June were noticeably different and was likely due to differences in weed cover and radiometric calibration error. Two key limitations of using Sentinel-2 satellite data are the requirement for cloud-free days and poorer spatial resolution (10 m^2 pixel). Nevertheless, open-source imagery, high spectral resolution, high spatial coverage and repeat sampling frequency, identify satellite imagery, such as Sentinel-2, as a potentially powerful tool for mapping aquatic vegetation at lake-wide scales. Additional work is required to explore the use of satellite imagery where *L. major* is submerged and the effects of water properties such as colour (Free *et al.* 2020).

Electronic data collection applications increased the efficiency of collecting, mapping and sharing data. Constraints on the data input fields reduced both errors and outliers and provided a basic facility to screen spatial data patterns upon collection. Secure data uploading at the moment of collection, allowed both field and office-based staff to view site data and images in real-time, improving decision making. Bluetooth connectivity to a hand-held GPS was required to ensure accurate GPS functioning, while a protective casing and water-proof tablet were essential for out-door use and wet conditions.

Currently, data is held in numerous disparate databases and exists in various formats that impede its use, retrieval and exchange. A data management plan is recommended, as is investigating the use of "*Dashboards*". Dashboards are specially designed user interfaces that summarise important data for managers as the data is generated. This would increase the interoperability and availability of the data, in line with best practice and expedite effective decision making (Groom *et al.* 2017).

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

4.1 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.

The aim of this work package is to provide an up-to-date distribution map of *L. major* in Lough Corrib. Distribution data collected during 2018 and 2019 are presented here, alongside historical distribution information.

4.2 Materials and methods

4.2.1 Mapping the lake-wide distribution of *L. major* (2005 to present)

L. major distribution data from this study (2018 and 2019), historical surveys and control operations were collated to provide a picture of *L. major's* distribution since its discovery in 2005. Distribution is reported across four different time periods, with a variety of sampling methods and efforts applied.

LARC 2018-2019

L. major distribution data was collected during 2018 and 2019, with methods discussed elsewhere in this report. These include; random sampling at 200 sites (Section 5.2.1), targeted sampling (Section 5.2.2), incidental sightings by the scientific and control teams (Section 3.2.6).

Post-CAISIE Survey 2013

A lake-wide survey was conducted in September 2013 to collect presence/absence data. Observations were made by snorkelling along pre-determined transects. The survey targeted areas that were considered vulnerable to infestation or had been previously infested.

CAISIE 2009-2012

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

IFI 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.

4.3 Results

4.3.1 *L. major* lake-wide distribution (2005 to present)

L. major distribution data recorded by the various IFI research projects and the control operations are shown in Figure 4.1. *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. Results show that *L. major's* current distribution in the middle lake is sporadic and characterised by isolated pockets occurring in Annaghdown and on the western shore, opposite Ballindiff Bay. *L. major* was absent from the lower lake and Ballindiff Bay in 2018 and 2019. However, the team recorded *L. major* at a southern site on the western shore in the middle lake showing that it continues to expand towards the lower lake. A relatively low occurrence was also apparent along the northern shore of the upper lake and around its offshore islands.

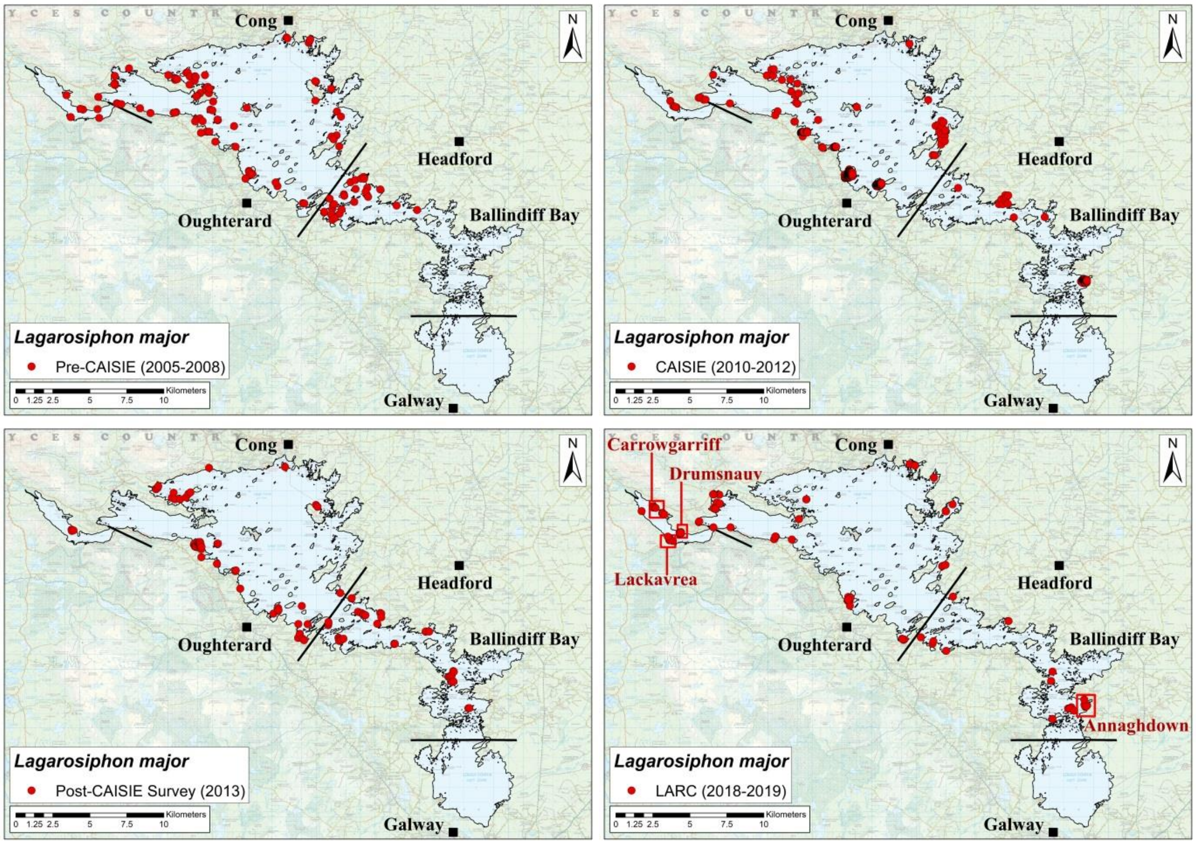

Figure 4.1. Distribution of *L. major* in Lough Corrib during IFI research projects, 2005-2019.The thick black lines represent the boundaries of the western arm, upper, middle and lower lakes.

4.3.2 *L. major* distribution in selected study areas, 2019

The distribution and area covered by *L. major* was estimated and mapped in detail across four study areas. *L. major* covered an estimated area of 3,980 m^2, 6,205 m^2, 29,116 m^2 and 30,981 m^2 in Carrowgarriff, Lackavrea, Annaghdown and Drumsnauv respectively (Figure 4.2).

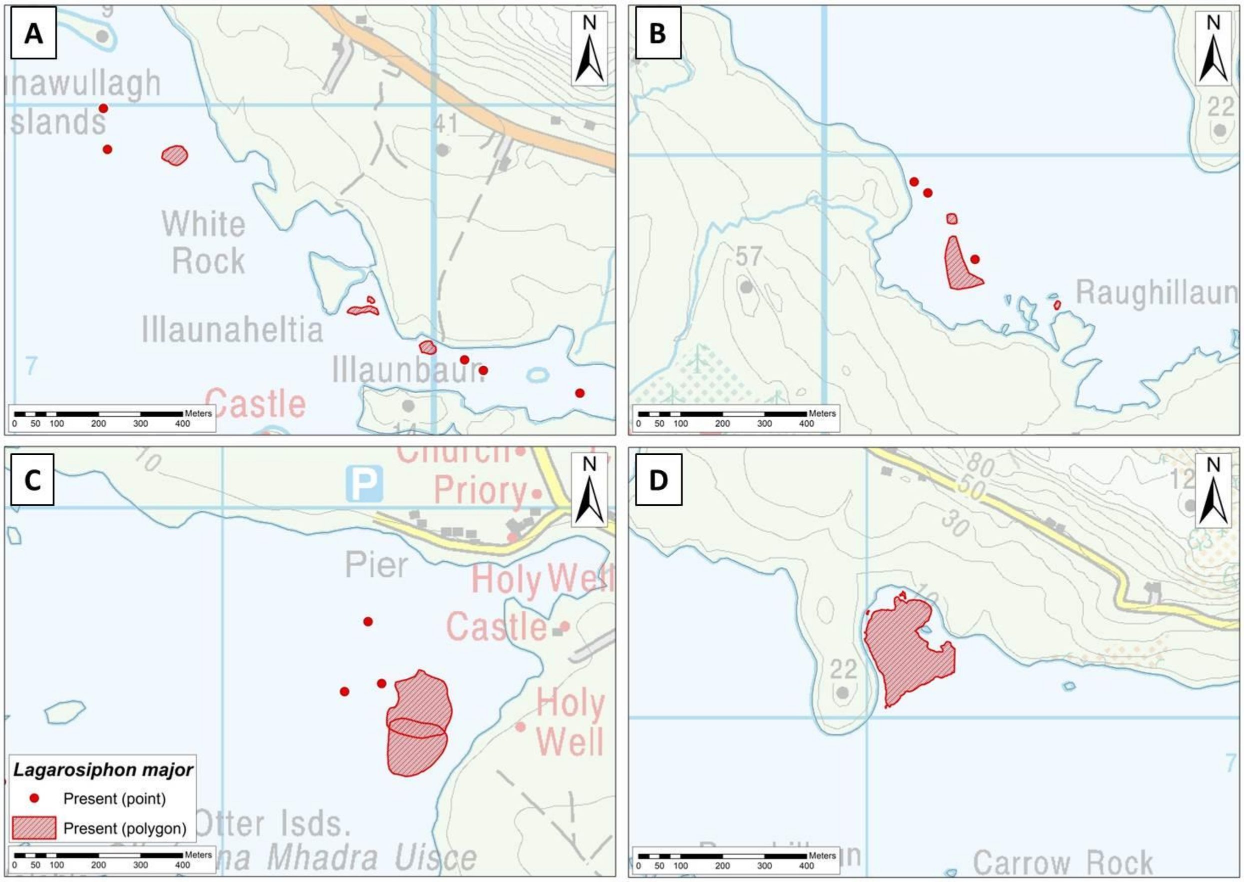

Figure 4.2. *L. major* distribution in A. Carrowgarriff, B. Lackavrea C. Annaghdown and D. Drumsnauv.

4.4 Discussion

Lake-wide results show that *L. major* went 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, its distribution has spread slowly towards the lower lake. There are still no records of *L. major* in the lower lake to date, however, data collected in 2019 show that the southern edge of its distribution is approaching this boundary.

The distribution of *L. major* at the north-western and south-eastern edges of its distribution show that it can proliferate in both areas with large stands *circa.* 30,000 m^2 recorded in both Drumsnauv and Annaghdown.

Extensive distribution mapping will be carried out in 2020 using the modern survey techniques and data collection applications.

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

5.1 Introduction

Lough Corrib is a large lake that varies greatly in terms of habitat and environmental variables from north to south and east to west (Krause and King 1994). *L. major* has successfully invaded sites in the western arm, as well as upper and middle lake (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 don't. Further to this, apparent declines, unrelated to control operations, have recently been reported by the control team. 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 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).

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 (Mckee *et al.* 2002; Riis *et al.* 2012). In Lough Corrib *L. major* growth peaks during winter (Caffrey *et al.* 2011) when temperatures are typically below 10 ◦C. 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 (Bornette and Puijalon 2011;Hussner *et al.* 2016; Hussner *et al.* 2015). 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 (Berry and Dabrowski 2007; Krause and King 1994), 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). For example researchers have 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).

Sediment characteristics affect submersed aquatic plants 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* shows a preference for sheltered sites with fine sediment (Howard-Williams and Davies 1988). Furthermore, *L. major* biomass and 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.

The ultimate aim of this work package is to address the knowledge gap in relation to the effects of habitat and environmental variables on the establishment and persistence of *L. major* in Lough Corrib. To date a significant amount of literature has been reviewed and data has been collected for a range of variables. Preliminary results are summarized and the possible relevance of each factor is discussed in relation to the existing literature. This work will be extended in 2020 with statistical modelling factors identified here, at differing spatial scales.

5.2 Materials & methods

5.2.1 Lake-wide survey

The lake was sampled at 200 locations between January and April 2019 using a stratified random sampling design in areas <12 m deep (Figure 5.1).

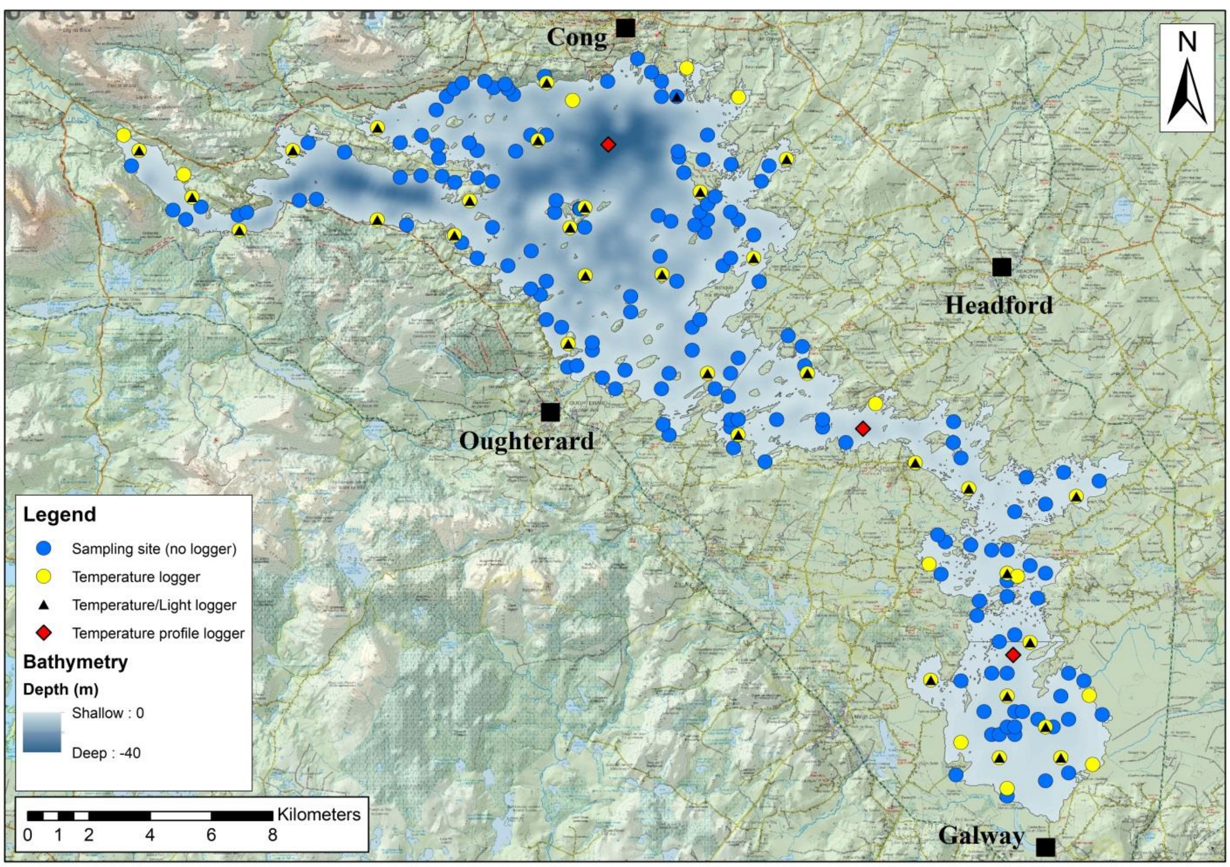

Figure 5.1. Sampling sites for *L. major* survey on Lough Corrib. Loggers (temperature and temperature/light) and thermistor string locations are also shown.

Macrophytes and habitat

Percentage cover of macrophytes and substrate type were recorded at each site using a 1 m^2 quadrat, using underwater video imagery and lighting. Four replicates were undertaken at each site. Dominant substrate was confirmed using a grab sampler. Subsequently, all available *L. major* datasets (2005-2019) were collated to inform the identification of spatial patterns in *L. major* distribution and its habitat preferences (see Section 4: for data collection methods).

Temperature and light intensity

Loggers were deployed across the lake (Figure 5.1). Temperature loggers (n=38) were deployed on the lake bed logged every 6 hours from December 2018 to October 2019. Temperature/light loggers (n=31) were subsequently deployed on a sub-set of the same moorings one meter below the lake surface. They logged every 20 minutes, from July to October 2019 (Figure 5.2). Monthly mean values were calculated and spatially interpolated for each logger variable.

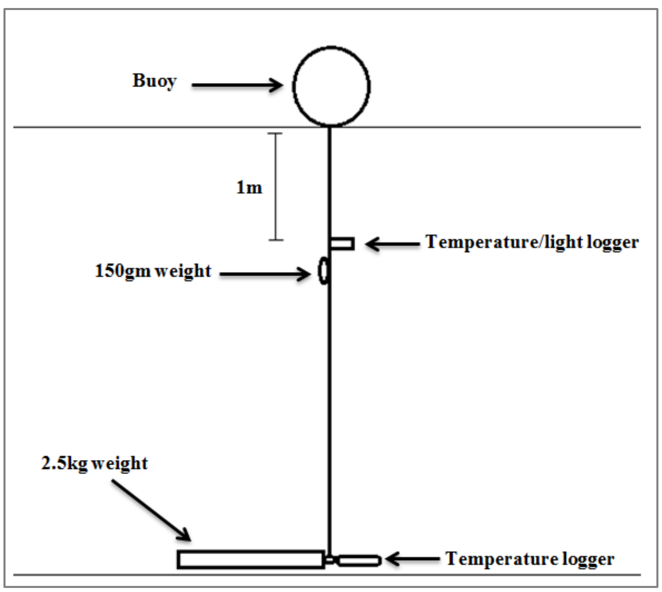

Figure 5.2. Graphic of the lake-wide logger moorings.

Temperature profiles

Three thermistor strings were deployed at the deepest points in the upper, middle and lower lakes from December 2018 to October 2019 (Figure 5.1). The thermistor strings were rigged at the following depth intervals in the upper lake (0.5, 3.0, 6.0, 12.0, 18.0, 24.0, 42.0 m); middle lake (0.5, 2.0, 4.0, 6.0 m) and lower lake (0.5, 2.0, 4.0 m).

Physico-chemical parameters

Water transparency (Secchi disc) and depth were recorded at each sampling site (Figure 5.1). Mean monthly pH and total alkalinity (as $CaCO_3$) were downloaded from the Environmental Protection Agency (EPA) river and lake monitoring sites for 2019 and spatially interpolated (Figure 5.3).

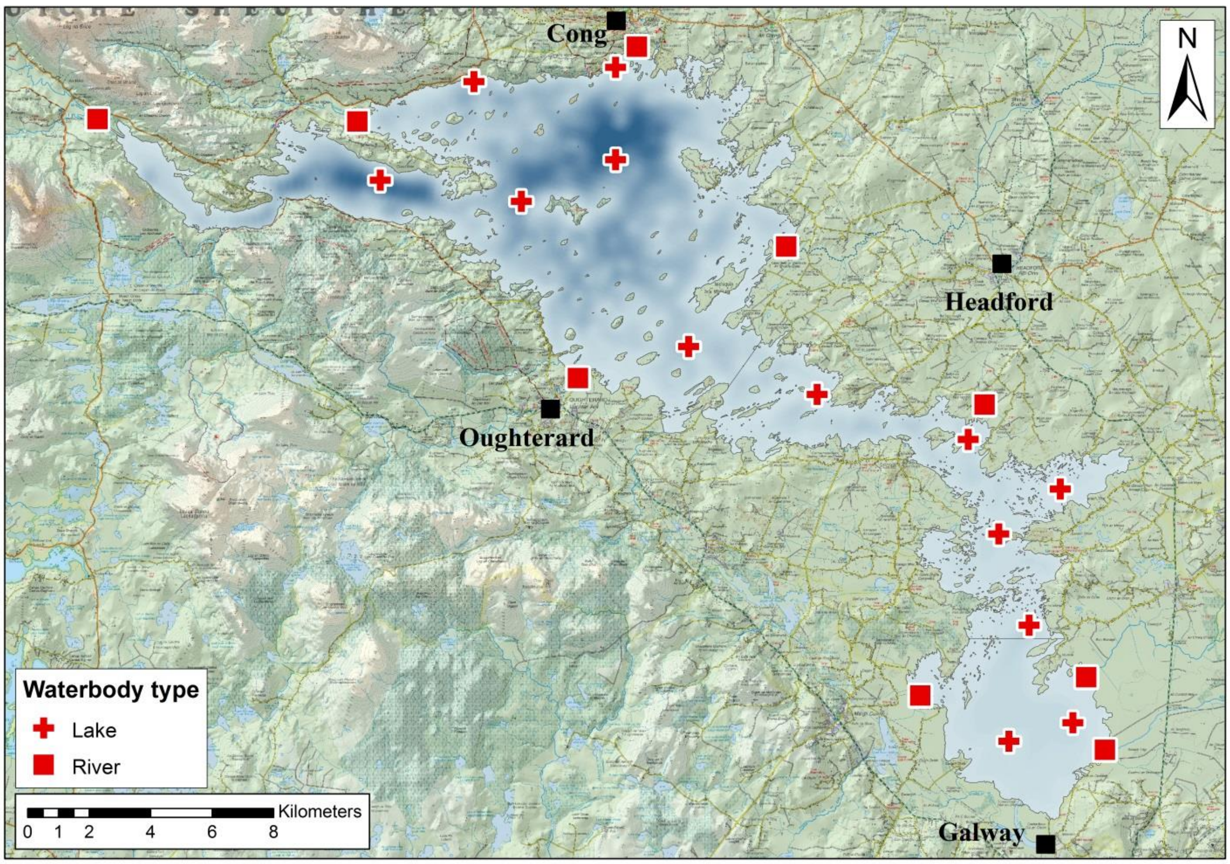

Figure 5.3. EPA lake and river monitoring sites where alkalinity (as $CaCO_3$) and pH were measured in 2019.

5.2.2 Detailed study of selected areas

A series of more detailed systematic and targeted sampling designs were deployed in three study areas. The areas selected, represent the upper and lower extent of *L. major* in the lake (Figure 5.4). Information on macrophytes, habitat and environmental variables were collected in each area.

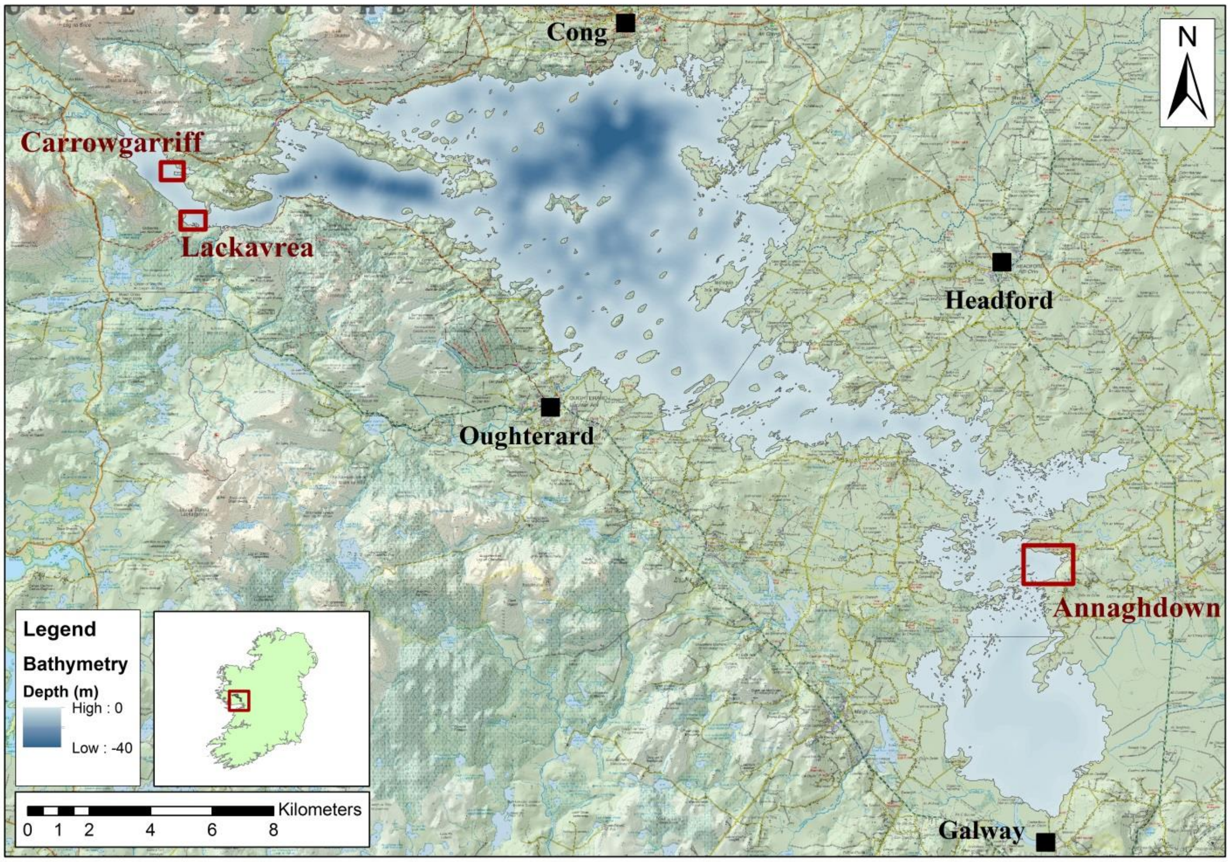

Figure 5.4. Detailed study areas on Lough Corrib; Carrowgarriff, Lackavrea and Annaghdown (highlighted in red).

Macrophytes and habitat

Based on hydroacoustic results (see Section 3.3.2), targeted sampling of macrophytes and substrate was carried out between the 21st to 31st October, 2019 in the three detailed study areas. Three replicate grapnel hook samples were used to record *L. major* presence/absence at 44 sites. Substrate type was also sampled at these locations using a Van Veen grab sampler (Figure 5.5).

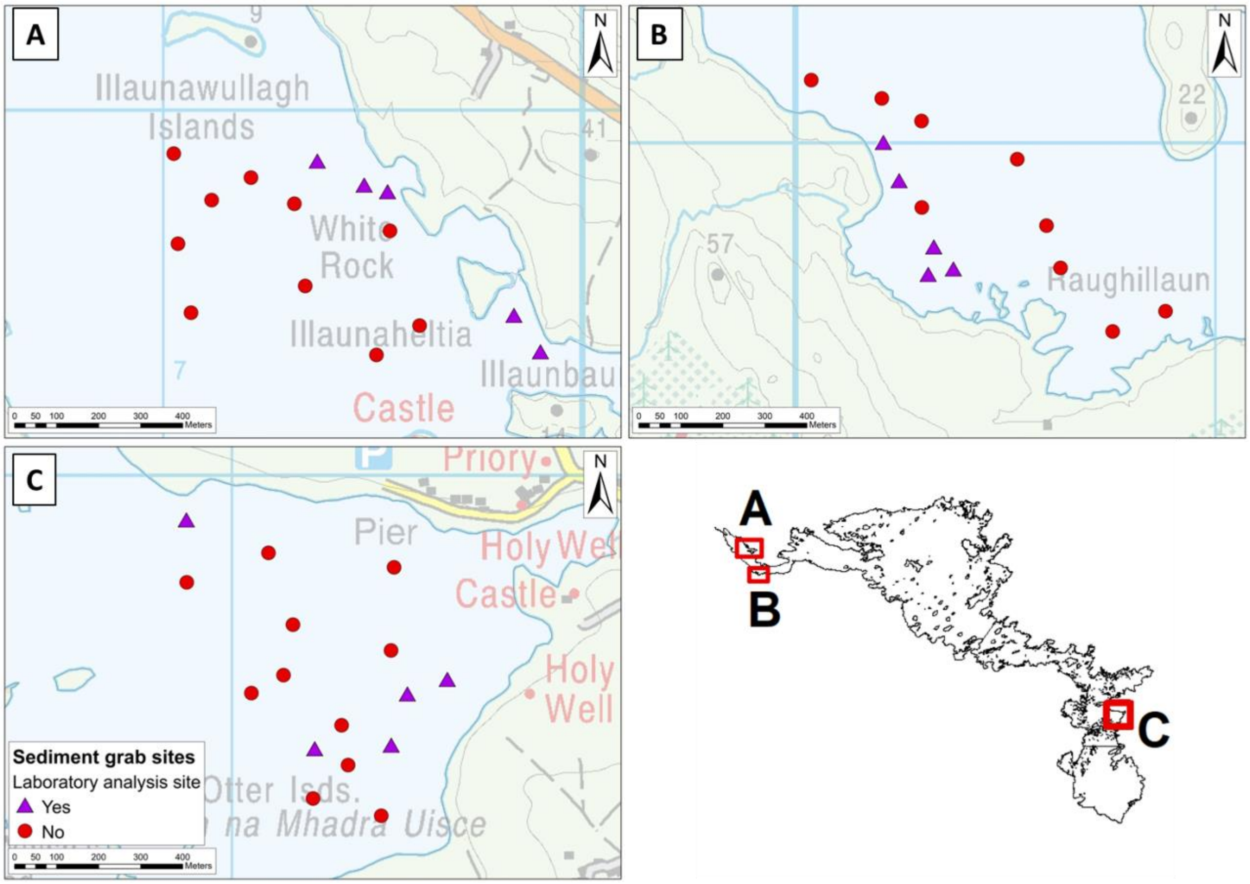

Figure 5.5. Sediment sampling sites at: A. Carrowgarriff, B. Lackavrea and C. Annaghdown.

Sediment analysis

A Van Veen grab was used to collect sediment samples (≥0.5 kg) from five sites per study area (Figure 5.5). Samples were stored at 4 °C in a dark container prior to analysis. The parameters tested are listed in Appendix 9.3. Total Nitrogen was determined using photometry. Carbon was determined using infrared spectroscopy and organic dry matter by gravimetry. All other elements were determined using spectrometry (ICP-OES).

Temperature and light intensity

Temperature/light loggers were deployed between the 16th of August and the 27th of September 2019, at 27 evenly spaced sites in the three study areas. Loggers were rigged to sit 1 m off the bottom in an effort to record conditions experienced by newly establishing shoots (Figure 5.6).

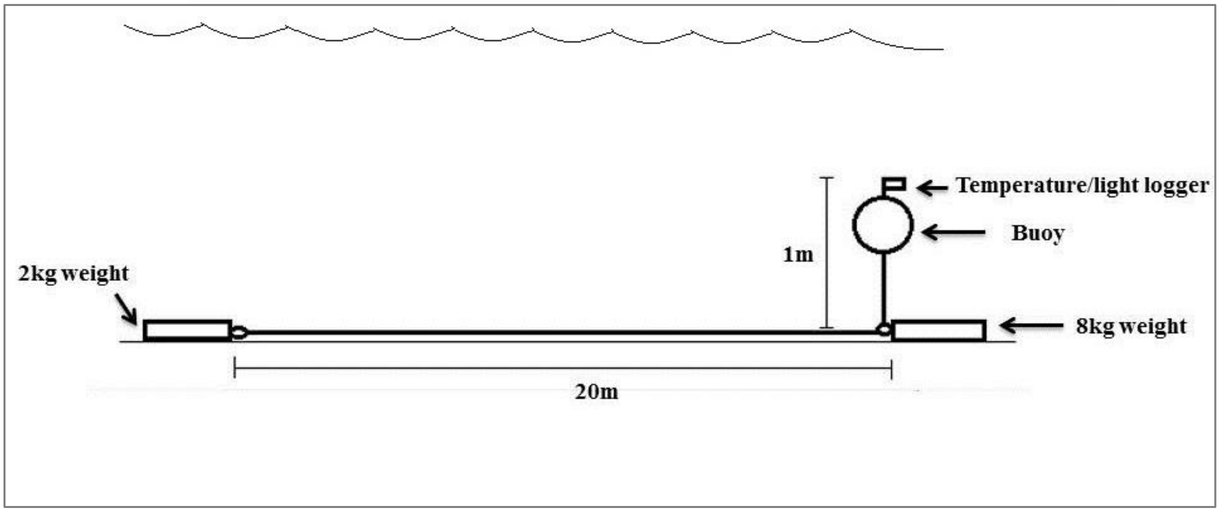

Figure 5.6. Graphic of the logger moorings in selected areas (20 m rope for retrieval).

5.3 Results

5.3.1 Lake-wide Survey

Macrophytes and *L. major* presence/absence

Macrophytes were recorded at 79% of the sites surveyed. Charophytes were most abundant and were present at 46% of sites, followed by *Elodea canadensis* 11%, *Myriophyllum* spp. 5%, *Potamogeton* spp. 3% and *L. major* 1.5%. *L. major* was recorded in the western arm, upper and middle sections of Lough Corrib and was not found in the lower lake. Charophytes were present at 74%, 61% and 30% of sites in the lower, middle and upper lake respectively but only 9% of sites in the western arm.

The lake-wide data collected and collate show that *L. major* is absent from the lower lake and Ballindiff Bay (Figure 5.7). *L. major's* distribution in the middle lake is sporadic with larger isolated pockets occurring in Annaghdown and on the western shore, opposite Ballindiff Bay (Figure 5.7). A relatively low occurrence is also apparent along the exposed northern shore of the upper lake and around its offshore islands (Figure 5.7). In addition, *L. major* is shown to be absent from areas deeper than 7 m (Figure 5.7).

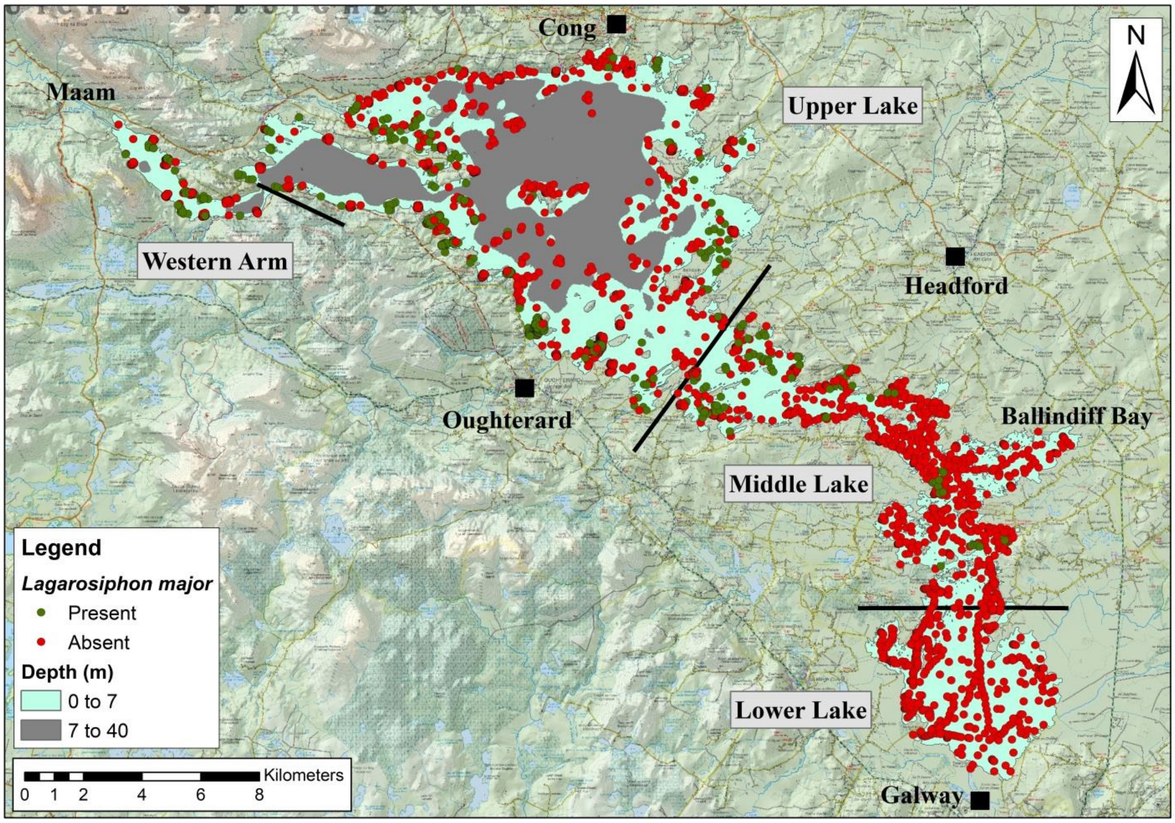

Figure 5.7. ***L. major*** **presence/ absence (2005-2019).**

L. major **habitat - substrate**

Substrate at sites in the western arm was predominantly composed of fine material such as mud/silt (36%) and sand (36%). In the upper lake, mud/silt (31%) and boulder/cobble/gravel (32%) were dominant at sites surveyed. Marl, a lime-rich mud, was present at 49% of sites in the middle lake, and 59% of sites in the lower lake.

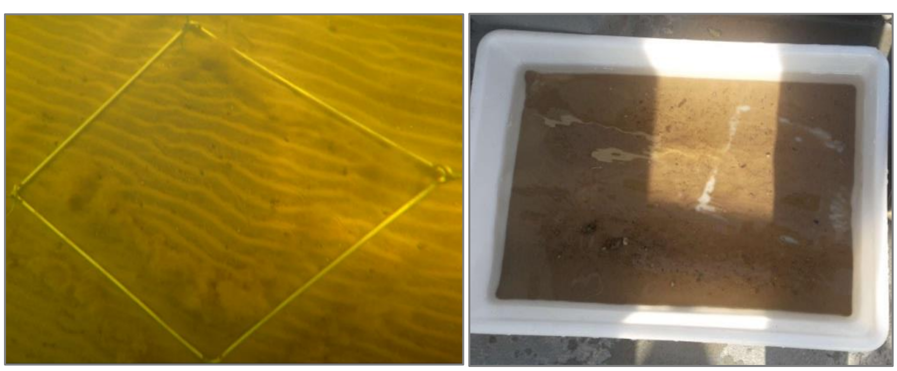

Plate 5.1. Quadrat sample showing sand and shells in the lower lake, (left) and a grab sample (right).

Lake-wide temperature

The temperature trends recorded at the sub-surface (1 m below the surface) generally reflect those observed by the benthic loggers (on the lake bed), hence only the benthic logger results are presented here (Figure 5.8). In general the upper lake warmed and cooled slower than elsewhere, while shallow areas, such as in the lower lake and eastern bays, were faster to warm in spring and cool down in autumn. Sites close to larger river inflows showed higher variation in temperature.

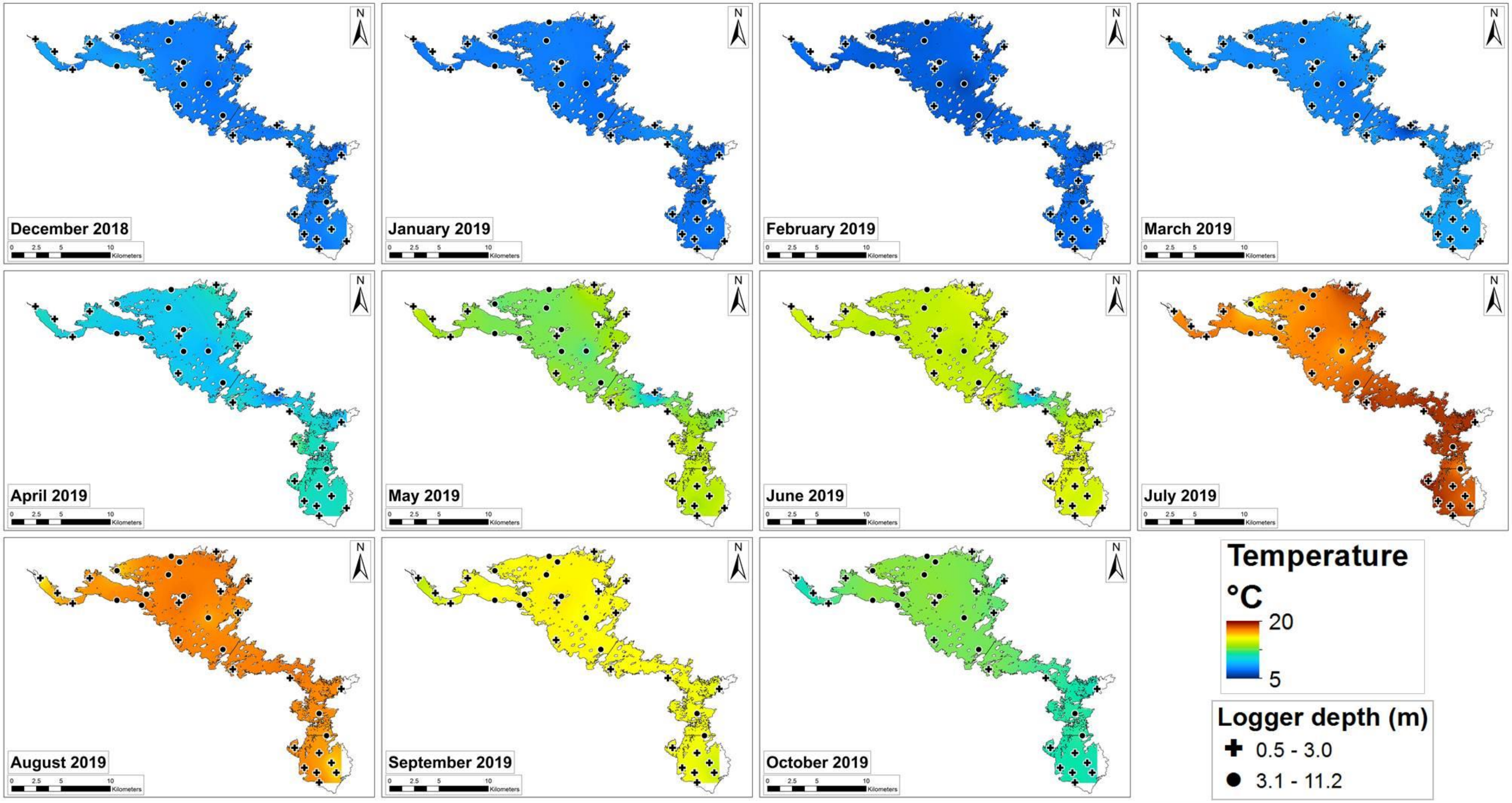

Figure 5.8. Interpolation of mean monthly temperature (°C) recorded at the lake bed, Lough Corrib December 2018 – October 2019.

Temperature profiles

Data from the three temperature profiles show that the lake remained well mixed throughout the year. Across the depths sampled water temperature ranged from 5.08-20.64 °C in the upper lake, 3.63-21.07 °C in the middle lake and 2.57-20.85 °C in the lower lake (Figure 5.9). The minimum water temperature in the upper and lower lake was recorded in February, and in March for the middle lake. The maximum temperature was recorded in the upper lake in July, and in August for the middle and lower lakes.

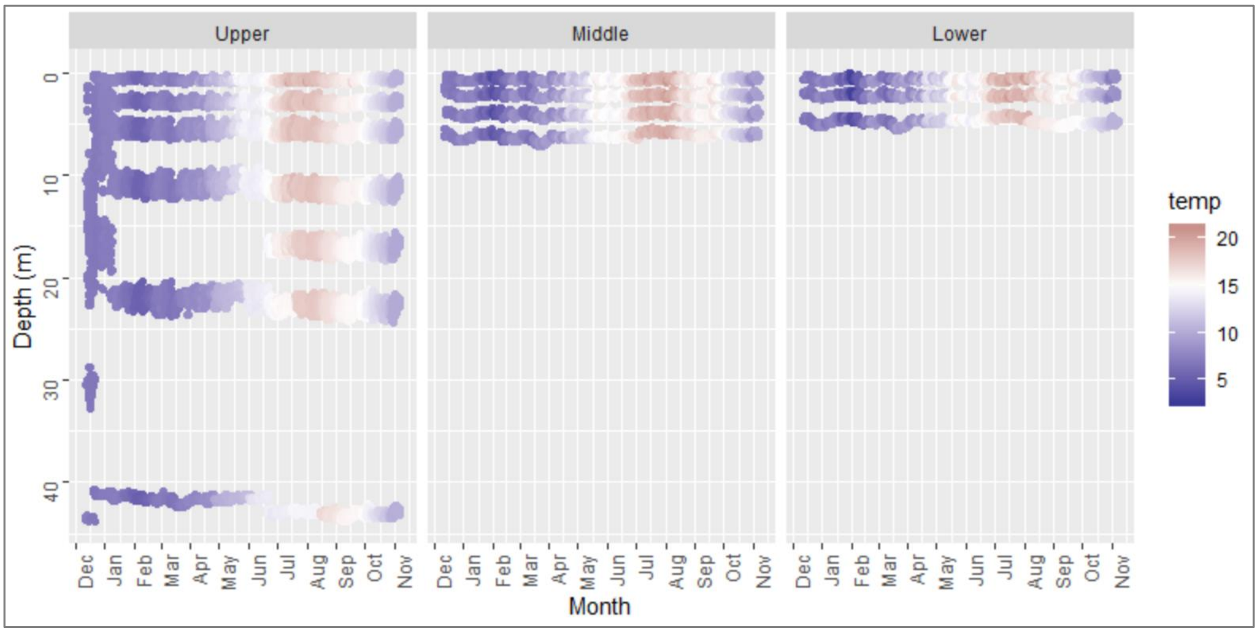

Figure 5.9. Temperature (°C) profile at the deepest point of the upper, middle and lower lakes

Light intensity

Light intensity (lux) decreased from July to October, in line with seasonal day length. Light intensity was generally lowest in the western arm and the eastern side of the lower lake and highest in the middle lake (Figure 5.10). Light intensity was also low in the east of the lower lake in August and September, it is possible that this is due to turbidity from the inflowing Clare River as observed from satellite data (Figure 5.10).

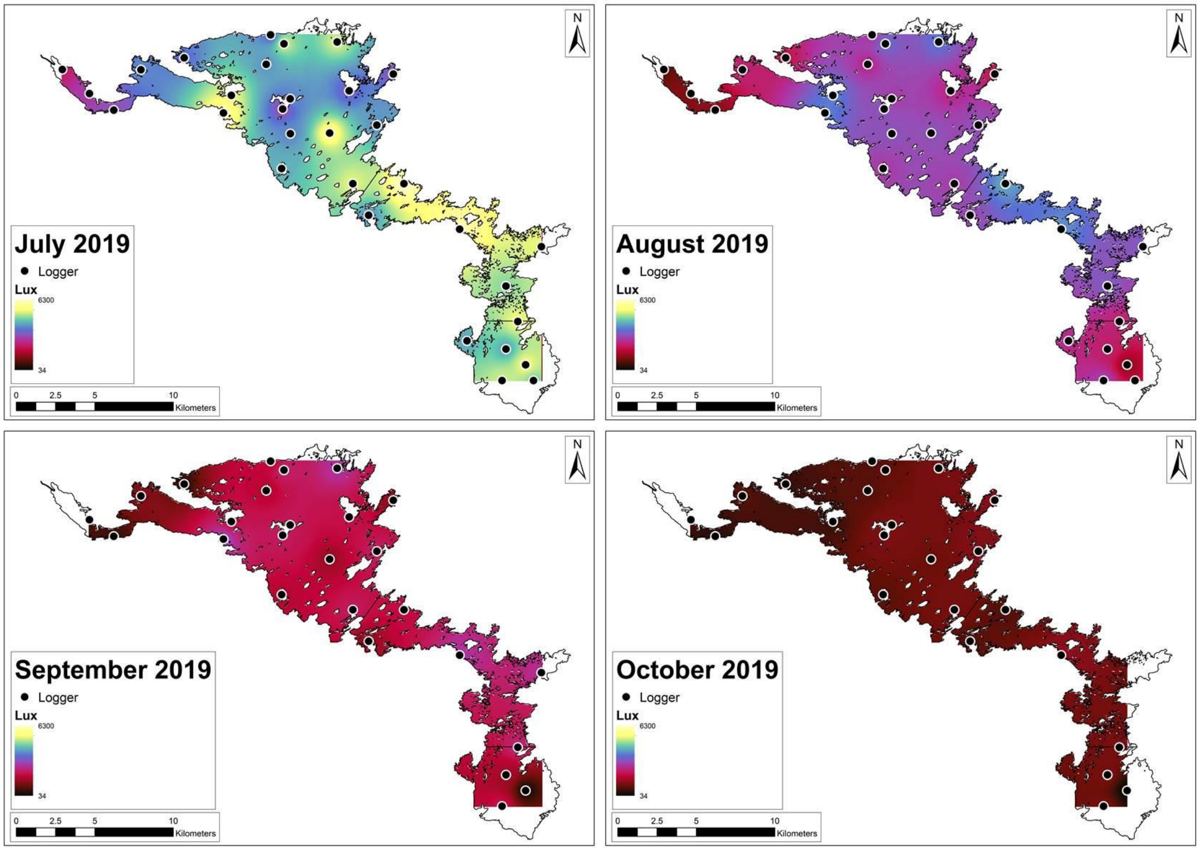

Figure 5.10. Interpolation of mean monthly light intensity (lux) recorded at 1 m below the surface, Lough Corrib July to August 2019.

Physico-chemical parameters

Secchi disc depth ranged from 2 m in the western arm and lower lake, to 7.2 m in the upper lake.

A wide range of alkalinity values were recorded across the lake and inflowing rivers (5 - 355 $CaCO_3$ mg/l) (Figure 5.11). Data shows a general gradient of increasing alkalinity from west to east. Alkalinity was consistently lower in the western arm, with the highest values recorded on the eastern side, typically near the inflowing Clare and Black Rivers in the lower and upper lakes respectively.

pH displayed similar spatial patterns to alkalinity. There was a general gradient of increasing pH from west to east with consistently low values recorded in the western arm and at river inflows on the western shore (Figure 5.12). The pH of the middle and lower lake displayed seasonal patterns with pH elevated during the summer months.

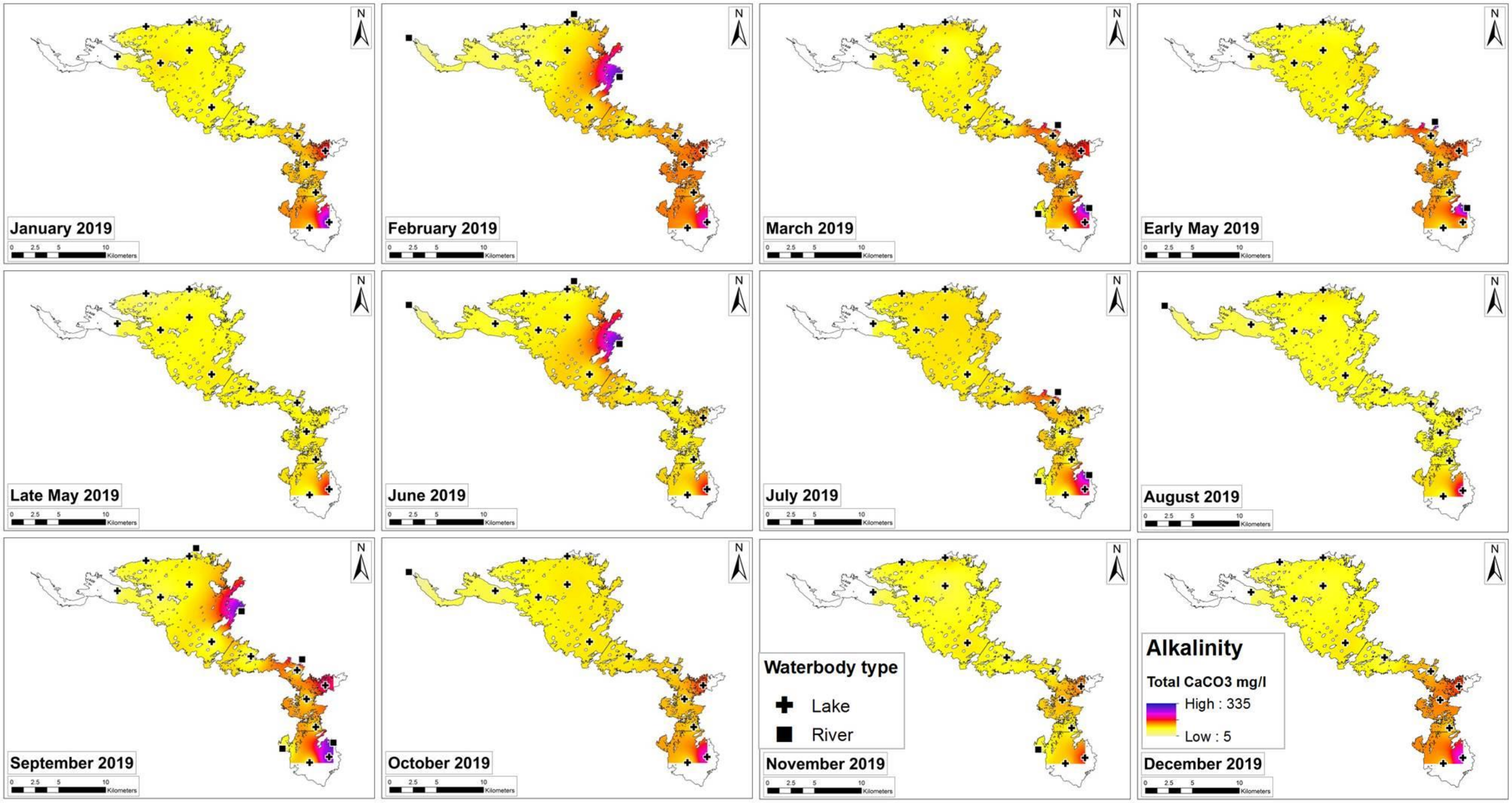

Figure 5.11. Interpolation of alkalinity data (monthly mean) from Lough Corrib and inflowing rivers, 2019. Data source EPA.

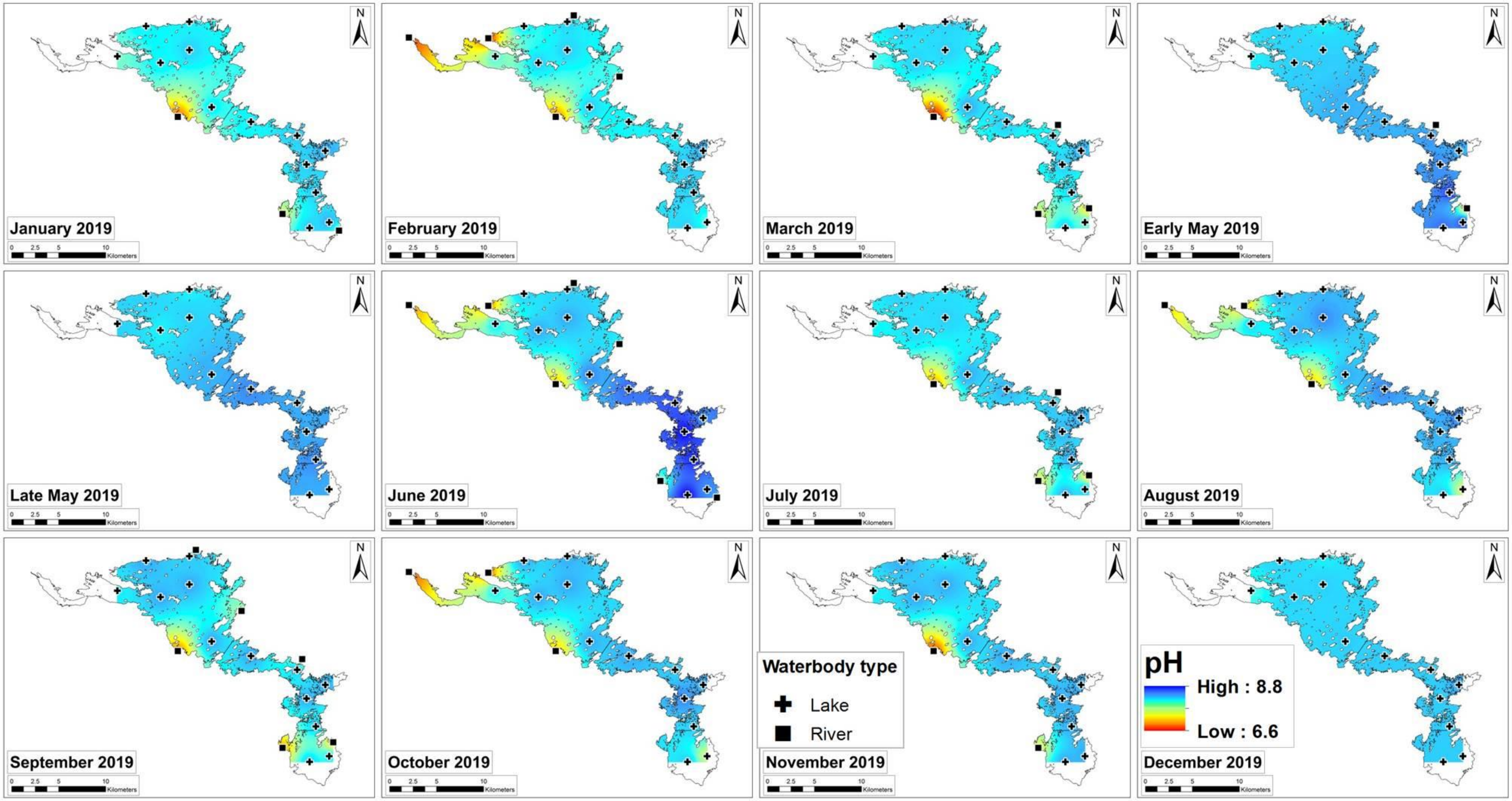

Figure 5.12. Interpolation of pH data (monthly mean) from Lough Corrib and inflowing rivers, 2019. Data source EPA.

5.3.2 Detailed study of selected areas

Macrophytes and *L. major* presence/absence

A wide variety of plant species were recorded at Annaghdown with charophytes recorded at all sites. Carrowgarriff and Lackavrea were sparsely vegetated and charophytes were absent from most sites (see Appendix 9.4, Appendix 9.5 and Appendix 9.6). Although not tested here, preliminary results appear to support the idea that *L. major* presence/absence may be related to shelter from the prevailing south-westerly winds (Figure 5.13).

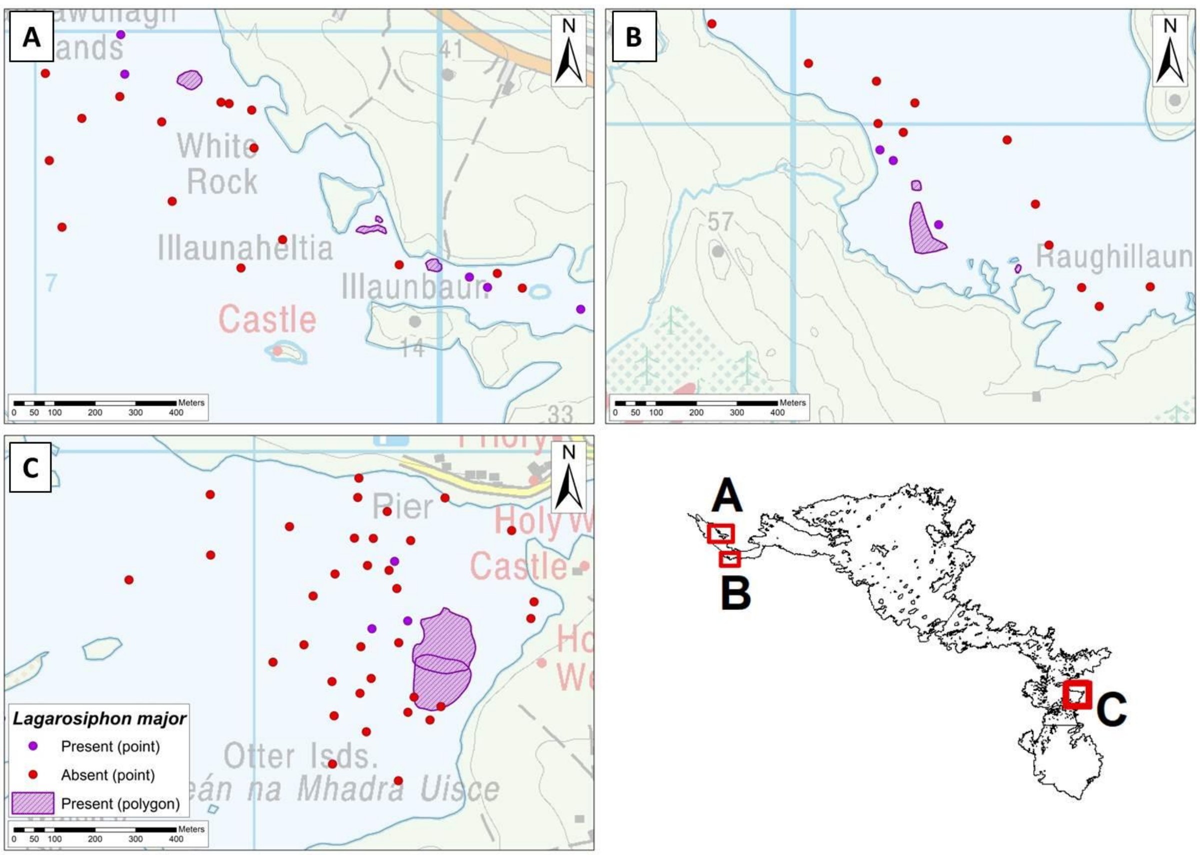

Figure 5.13. *L. major* presence/absence at A. Carrowgarriff, B. Lackavrea and C. Annaghdown.

Depth

Bathymetric models showed that *L. major* displayed different colonisation depths in each bay; 1 to 3m in Lackavrea, 2 to 3m in Carrowgarriff and >4m in Annaghdown (see section 3.3.2).

Substrate

L. major was typically found growing on fine substrates (see Appendix 9.4, Appendix 9.5 and Appendix 9.6). Sediments ≤3 mm (silt, mud and clay) dominated in Carrowgarriff and Lackavrea while marl, a lime rich mud was found at all sites sampled in Annaghdown Bay (see Appendix 9.4, Appendix 9.5 and Appendix 9.6).

Sediment analysis

High concentrations of calcium and sodium were found in the marl sediment tested at Annaghdown. Iron, copper and phosphorus levels were similar across the study areas. Carbonates, total carbon, inorganic and organic carbon and total nitrogen were highest in Annaghdown. Percentage organic dry mass was lowest at Carrowgarriff and highest at Annaghdown (Appendix 9.7).

Temperature

Across the period sampled the mean site water temperature (measured at one meter above the lake bed) varied little (<1 °C) within and across the three study areas (Table 5.1). Annaghdown was the warmest site in August and September and the coolest in November.

Table 5.1. Minimum and maximum monthly temperatures (°C) for each bay (benthic mooring).

Sample period	August (16-31)			September (1-30)			October (1-31)			November (1-7)		
Temperature °C	Min	Max	Mean (± SD)	Min	Max	Mean (± SD)	Min	Max	Mean (± SD)	Min	Max	Mean (± SD)
Carrowgarriff	15.90	16.20	16.05 (±0.09)	15.04	15.27	15.13 (±0.08)	11.14	11.50	11.34 (±0.14)	9.19	9.55	9.38 (±0.14)
Lackavrea	16.18	16.62	16.38 (±0.13)	15.09	15.44	15.23 (±0.13)	11.57	11.75	11.65 (±0.05)	9.23	9.48	9.33 (±0.09)
Annaghdown	16.83	17.09	16.94 (±0.06)	15.68	15.96	15.80 (±0.07)	11.45	11.78	11.58 (±0.08)	9.20	9.33	9.24 (±0.04)

Light intensity

Across the three study areas sampled, light intensity (lux) decreased with depth. However, differences in light intensity not associated with depth were also observed (Figure 5.14).

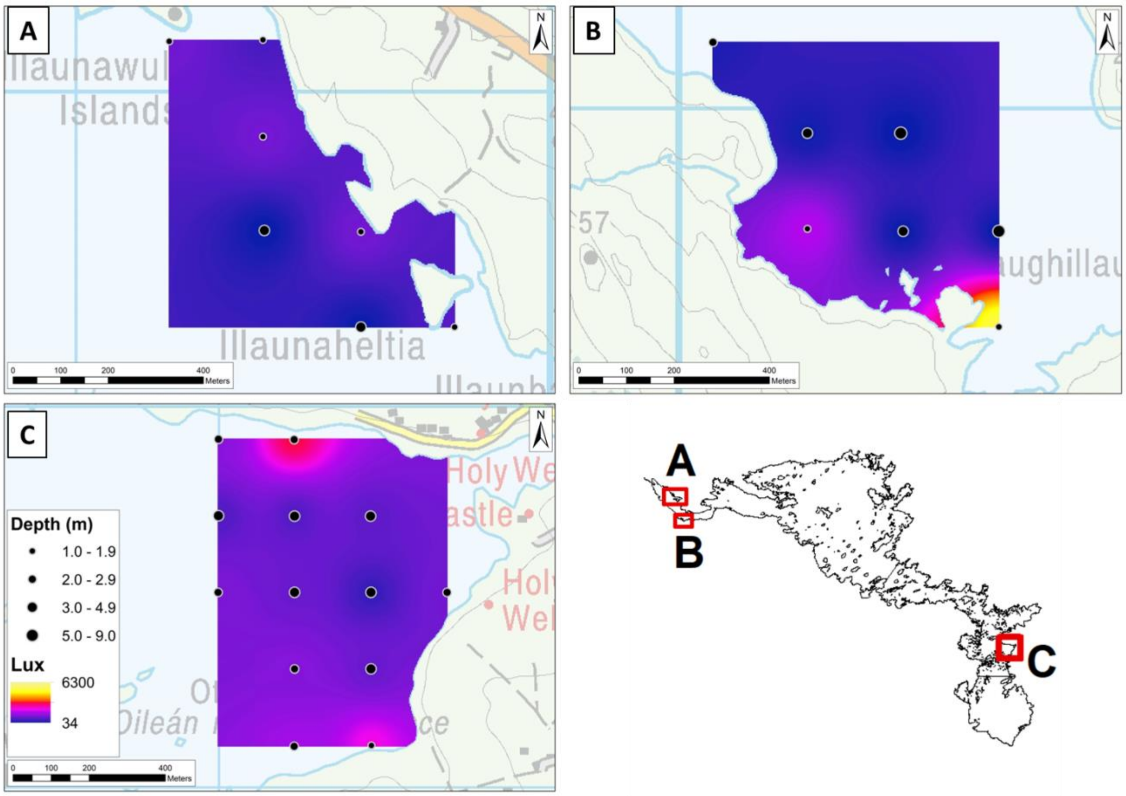

Figure 5.14. Interpolation of mean monthly light intensity (lux) recorded at 1 m above the lake bed in Carrowgarriff, Lackavrea and Annaghdown from 17 September to 17 October, 2019.

5.4 Discussion

An extensive literature review alongside the preliminary exploration of habitat and environmental factors indicates that shelter, silty substrate and depth may be important factors that influence *L. major* distribution at both large and small scales (Caffrey *et al.* 2011). In this study, *L. major* was generally absent from the north shore of the upper lake which is exposed to the prevailing south-westerly winds. Although limited, preliminary data from the detailed study areas also indicates that shelter may be important and the dominance of fine sediments where *L. major* occurs also supports this idea. Research elsewhere has shown that *L. major* displays maximum biomass and heights in sheltered areas (fetch <8 km), with *L. major* absent in areas with wind fetch greater than 10 km (Howard-Williams and Davies 1988). Consequently fetch, substrate and depth should be included in the statistical models in 2020.

In the detailed study areas (Carrowgarriff, Lackavrea and Annaghdown), *L. major* occurred in relatively narrow, study area specific, depth zones. Despite an abundance of shallower water in Annaghdown, *L. major* was found growing 1 m deeper than in the other two study areas. Interestingly, light intensity was higher in Annaghdown relative to the other sites. Therefore light may be an important factor determining the colonisation depth of *L. major* at sites in Lough Corrib. However, at the lake-wide scale, *L. major* was recorded at sites that reported a range of light intensity and Secchi disc readings. *L. major* displays high plasticity for light (Riis *et al.* 2010) and therefore light may not be a factor determining its lake-wide distribution. This preliminary result indicates that light should also be tested in statistical models that account for spatial dependency.

Temperature can significantly affect plant morphology and biomass production (Barko and Smart 1981). In this study temperature variations were only reported at the lake-wide scale. Shallow areas and areas near rivers reported more extreme values than deeper areas which were found to heat up and cool down slowly. All temperatures recorded in this study were within the range where *L. major* can sustain growth (Mckee *et al.* 2002; Riis *et al.* 2012). Therefore it's unlikely that temperature is a key determinant of *L. major's* distribution in Lough Corrib. However, little is known about *L. major* growth at the lower end of its temperature range and further research is required. Given the fundamental importance of temperature it is recommend that it be tested during model development in 2020.

Alkalinity and pH, display spatial patterns which indicate they may be important in determining the distribution of *L. major* in Lough Corrib. Specifically, high alkalinity in the lower lake and Ballindiff Bay and low pH values near a number of inflows. Alkalinity, pH and temperature are directly related to free CO_2 and HCO_3^- concentrations (Christensen *et al.* 2013; Sand-Jensen *et al.* 2019). Plants adapted to calcareous waters can use HCO_3^- as a carbon source (Bain and Proctor 1980; Yin *et al.* 2017). Differences in HCO_3^- use efficiencies across alkalinities can influence species interactions and distribution (Cavalli *et al.* 2012; Yin *et al.* 2017). *L. major* grown at low alkalinity 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).

The availability of free CO_2, nitrogen (N) and phosphorous (P), often limit submerged aquatic plant growth (Bornette and Puijalon 2011; Andreas Hussner *et al.* 2016; Hussner *et al.* 2015). Indeed these elements were important in controlling *L. major* size in New Zealand (Riis *et al.* 2010). Adapted to low nutrient and high pH and alkalinity conditions, charophytes are dominant in the lower lake and Ballindiff Bay. Their dominance in such conditions is attributed to 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). In this study, there appeared to be no obvious link between *L. major* and sediment nutrient status within the study areas. However, more data is required and it should also be remembered that rooted macrophytes gather nutrients from the water column as well as sediments. Across the three study areas, Annaghdown sediments exhibited higher levels of N and calcium (Ca), similar levels of P and lower levels of iron (Fe). A shift in macrophyte communities from charophyte dominance to canopy-forming and floating plant species is commonly stimulated by increases in N and P (Bakker *et al.* 2013). Therefore, nutrient enrichment at high alkalinity sites may shift conditions from those favouring charophyte growth towards those that favour the growth of *L. major;* however more research is needed to confirm this.

This study concludes that free CO_2, pH, alkalinity, fetch, silty substrate, light and temperature are factors that should be modelled to investigate their relative importance in determining *L. major's* distribution. Preliminary data and existing research also indicate that their importance may be scale dependent. An extensive review of the literature also supports this approach and also point to the importance of including key phytonutrients N and P.

6: An assessment of the effectiveness of an Aquatic Weed Harvester

6.1 Introduction

Extensive control operations are undertaken annually to manage *Lagarosiphon major* in Lough Corrib by a small team funded by IFI, OPW, NPWS and Galway County Council. Mechanical cutting is used to remove large volumes of weed from infested areas during the winter months. Currently there are two weed-cutting boats, each one fitted with trailing V-blades and a forklift. The trailing V-blades cut the weed at its base, enabling it to float to the surface, where it is gathered using a forklift. The forklift then loads the weed onto a boat, to be transported ashore for composting.

This work involves a significant amount of manual handling, whilst the boats, commissioned in 2008, present with frequent mechanical issues. This has increased maintenance costs and number of down days (Moran, H. *pers. comm*.). In an effort to address these issues, discussions were held with the control team and the IFI research team. Discussions were also held with engineers in University College Dublin, to explore how the more laborious aspects of this work could be automated. From these discussions, it was apparent that a suitable solution would not be readily found within the allocated time and financial resources.

During 2019, Oirbsean, the company contracted to carry out the *L. major* control programme, commenced a trial using a Berky Aquatic Weed Harvester 6450. This harvester has a conveyor belt and large storage capacity. These design aspects have potential to reduce the manual handling required to complete harvesting and transfer to shore. However, the harvester trialled only cuts to a depth of 1.8 m and consequently, may prove less effective than the trailing V-blades that cut the weed at its base. Trailing V-blades are not suitable for all areas in Lough Corrib, mainly due to the nature of the substrate present in some places, with substrate dominated by large boulders being particularly difficult to negotiate. Consequently, the weed harvester trial conducted by Oirbsean targeted an area that proved difficult to control effectively with existing measures. Treating these areas is important as they are a likely source of wind-borne fragments that travel to, and infect adjacent sites.

This work aimed to assess the effectiveness of the mechanical aquatic weed harvester employed during the trial in treating a dense *L. major* infestation and reducing manual handling.

6.2 Materials & methods

6.2.1 Study Area and Sample Period

Drumsnauv Bay is a shallow (<3 m deep) horse-shoe shaped bay with a surface area of approximately 0.34 km^2 (Figure 6.1). The bay's mouth faces SSE and is generally sheltered from the prevailing SW winds. The shore is mostly composed of gravel, with an offshore substrate of dense mud. The bay also contains a number of small islands, surrounded by emergent vegetation. Pre-cut sampling was conducted between the 21st and 30th of May 2019. Cutting was undertaken over nine days, between the 5th and 20th of June 2019. Post-cut sampling took place between the 27th of June and 14th of August 2019.

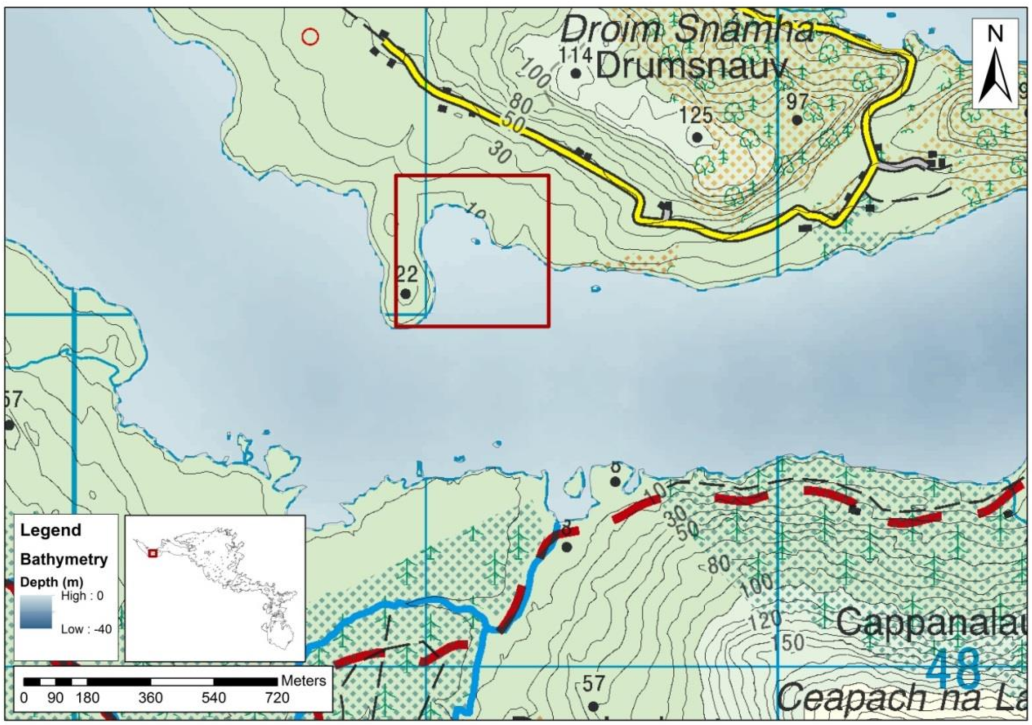

Figure 6.1. Drumsnauv Bay, Lough Corrib.

6.2.2 Berky Aquatic Weed Harvester 6450

Weed-cutting was conducted using a Berky Aquatic Weed Harvester 6450 (Plate 6.1). This harvester has a storage capacity of 40 m³, with an oscillating, U-shaped double knife (1.8 x 2.5 m) at the front and a conveyor belt to facilitate loading and unloading. The cutting speed and blade depth are adjustable and controlled by the operator.

Plate 6.1. Berky Aquatic Weed Harvester 6450 cutting *L. major* in Drumsnauv, June 2019.

6.2.3 Containment Measures

A buoyed containment net was set outside the bay to capture free-floating fragments that were not gathered by the harvester. The control team also gathered fragments on the water and along the shore using hand nets and forks.

6.2.4 Estimating the extent of *L. major*

Sentinel-2 satellite imagery was used to map and estimate the extent of *L. major* in Drumsnauv Bay, as suitable UAV imagery was not available.

Satellite Image Acquisition and Ground-truthing

Four ortho-images were downloaded based on the availability of cloud-free scenes and timing relative to harvesting (Table 6.1). Images were geo-referenced and the area, perimeter and relative density of *L. major* were estimated using the NDAVI and RGB ortho-mosaics (see Section 3.2.2). Analysis was bound by *L. major's* perimeter recorded on the 5th of June, to avoid the inclusion of other vegetation. The area and perimeter of *Dense* and *Sparse* vegetation was determined as described in Section 3.2.2.

Table 6.1. Details of satellite images downloaded (ESA Copernicus, Sentinel-2 data, 2019)

Sampling Occasion	Sensing date	Sensing time	Sentinel sensor	Processing level
Pre-cutting (8-months)	28/10/2018	11:43:49	S2B	L1C
During cutting	10/06/2019	11:46:37	S2A	L1C
Post-cutting (2-weeks)	03/07/2019	11:56:38	S2A	L1C
Post-cutting (2-months)	18/09/2019	11:46:34	S2A	L1C

6.2.5 Quantify fragmentation

Fragments generated by cutting (5th of June) were quantified using RGB orthomosaics generated by images captured at 30 m height by UAV flights. While cutting was underway, two replica automated flights were flown 2 hours and 45 minutes apart to obtain independent samples.

A study area of 8,121 m^2 was identified with high quality imagery (Figure 6.2). *L. major* fragments (≥0.1 m^2) were visually detectable and their outlines were traced. Fragment count, area, perimeter and % of sample area with fragments were then calculated. Identical patches of *L. major* identified during both UAV flights were assumed to be uncut stands and were removed from the analysis.

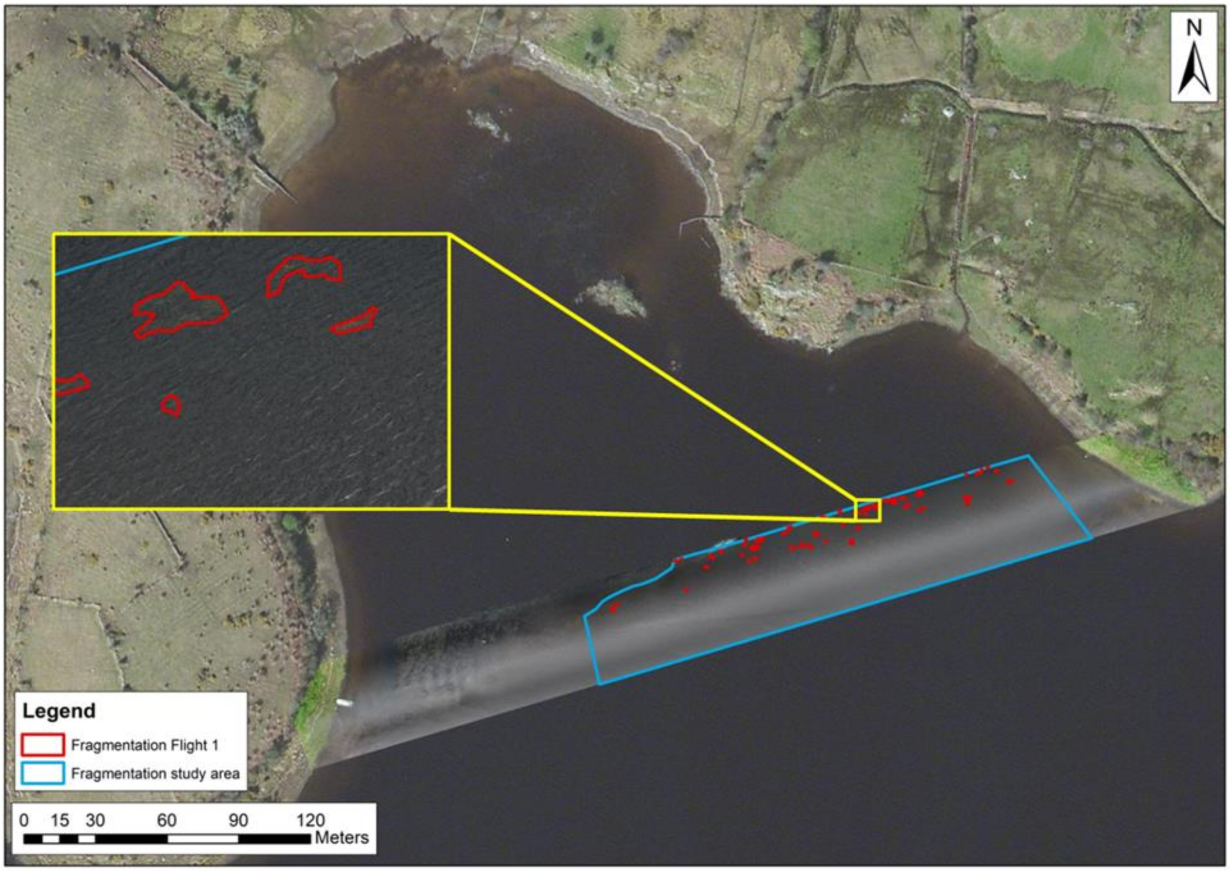

Figure 6.2. The study area analysed for *L. major* fragments outlined in blue. Yellow box shows close up of *L. major* fragments and polygons outlined in red.

6.2.6 Cut quality

The quality of the cut delivered by the blades was inspected to assess fragmentation risk and re-growth on the 27th of June 2019 using a ROV with HD camera. The camera was deployed at several locations within the zone shown in Figure 6.3.

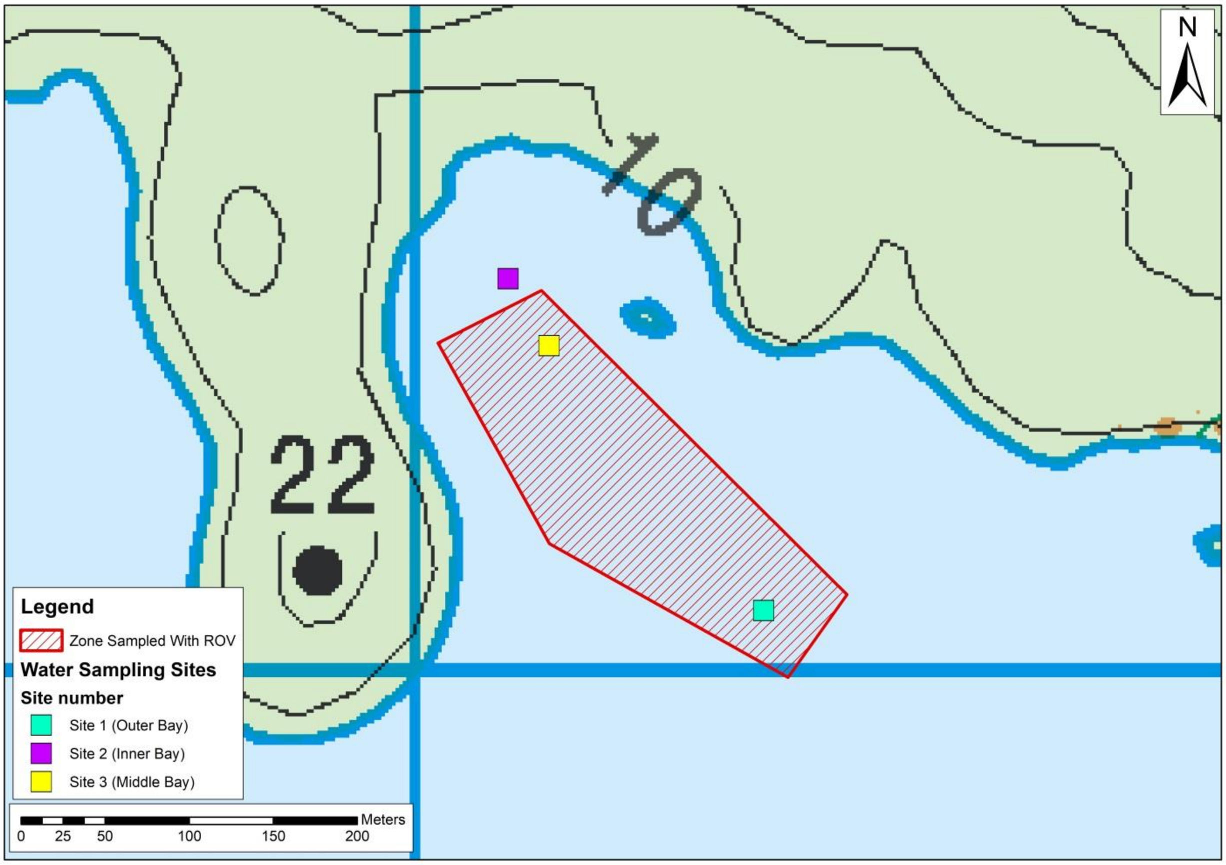

Figure 6.3. Area surveyed using the ROV and water sampling sites

6.2.7 Physicochemical parameters

A surface water sample was collected at three sites (Figure 6.3); pre-cutting (30th May), during-cutting (6th June) and post-cutting (27th June). Physicochemical analysis was conducted for; Total N (N mg/l), nitrate (N mg/l), nitrite (N mg/l), Total P (P mg/l), ammonium (NH_4 mg/l), chlorophyll *a* (ug/l). Turbidity (NTU) was measured at a higher frequency on the 6th of June (Time 0, +15 min, +45 mins, +1h 45 mins, +2 h 45 mins, +3 h 45 mins, +4 h 45 mins and +5 h 45 mins) at the middle bay site, to assess sediment re-suspension levels over the short-term.

6.3 Results

6.3.1 Estimating the extent of *L. major*

The area, perimeter and mean NDAVI estimates for *L. major* were initially reduced post-cut (Table 6.2 and Figure 6.4). Over a two week period, the area covered by *L. major* was reduced by 78% (Table 6.2) even though the harvester was unable to treat shallow areas where *L. major* was mixed with emergent vegetation (Figure 6.4).

Two months post-cut, *L. major* was found growing back in the area where it was first cut, with it re-establishing 10% of its original cover. However, NDAVI values indicated that *L. major* patches were less dense. (Figure 6.4B and D).

Three and a half months post-cut, *L. major* was found to have exceeded its original cover area by 9.2% (Table 6.2)

Table 6.2. Area, perimeter and mean NDAVI for *L. major*, calculated from satellite and UAV images.

Sampling Occasion	Date	Acquisition method	Mean NDAVI	Area of L. major (m^2)	Perimeter of L. major (m)
Pre-cutting (8-months)	28/10/2018	Satellite	-0.36	14,235	1,101
Pre-cutting (1-hour)	05/06/2019	UAV	NA	30,981	1,027
During cutting	10/06/2019	Satellite	-0.26	*19,747	*986
Post-cutting (2-weeks)	03/07/2019	Satellite	-0.41	6,811	807
Post-cutting (2-months)	18/09/2019	Satellite	-0.37	10,078	1,157
Post-cutting (3.5-months)	02/10/2019	UAV	NA	34,119	1,138

**Partial cutting had commenced during the weed harvester trial*

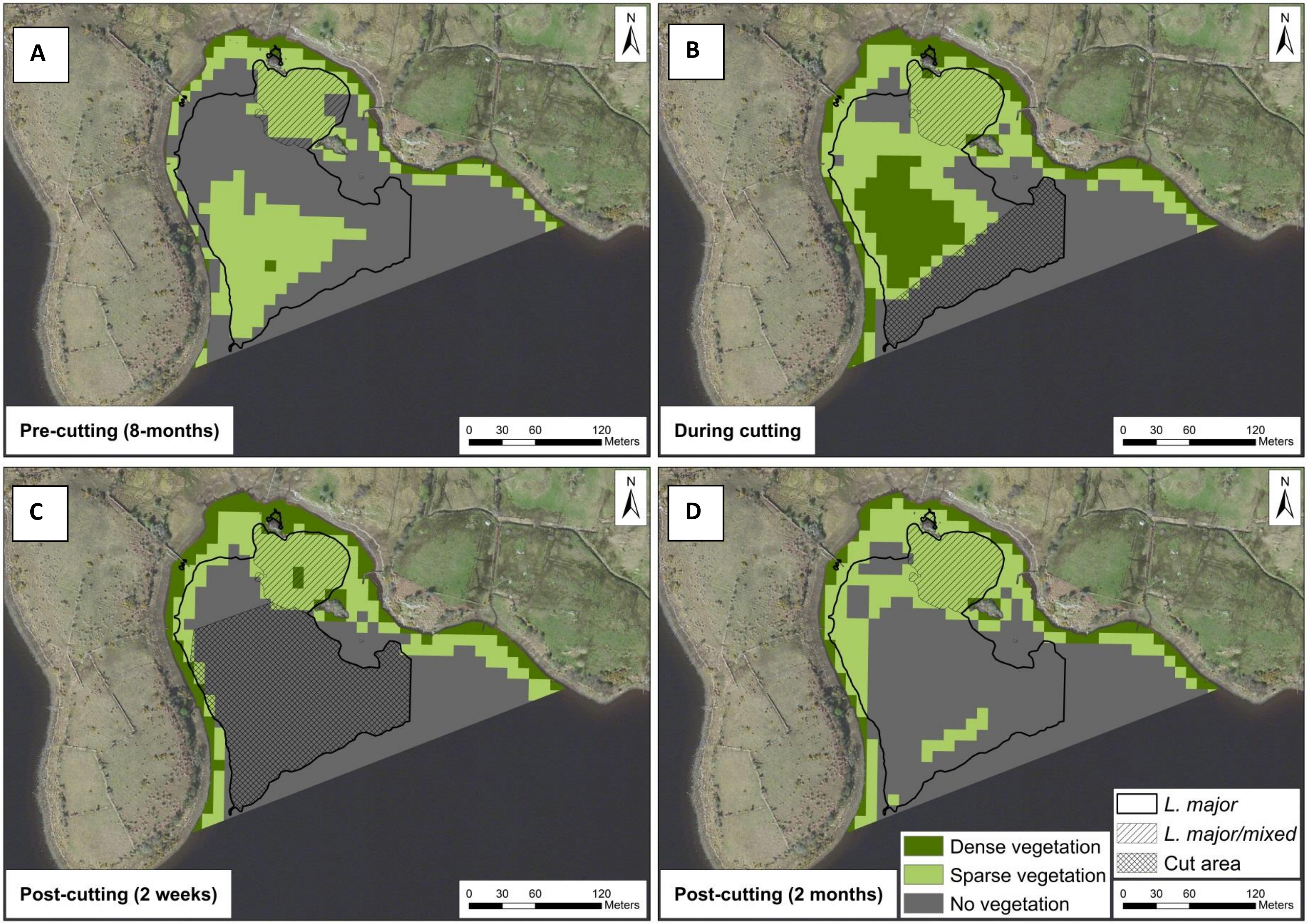

Figure 6.4. NDAVI calculated from Sentinel-2 images; (A) Pre-cutting (8-months), (B) During cutting, (C) Post-cutting (2-weeks) and (D) Post-cutting (2-months).

6.3.2 Quantify Fragmentation

On both sampling occasions 0.34% of the study area contained *L. major* fragments (Table 6.3 and Figure 6.5). Fragments ranged in size from the minimum size it was possible to visually detect of 0.10 m^2 to a maximum size of 4.31 m^2.

Table 6.3. *L. major* fragmentation estimates from two UAV flights

Flight no.	Fragment count	Max fragment size (m)	Min fragment size (m)	Median fragment size (m)	Total area of fragments (m^2)	Study area with fragments (%)
1	67	2.81	0.10	0.26	27.33	0.34
2	45	4.31	0.10	0.38	27.31	0.34

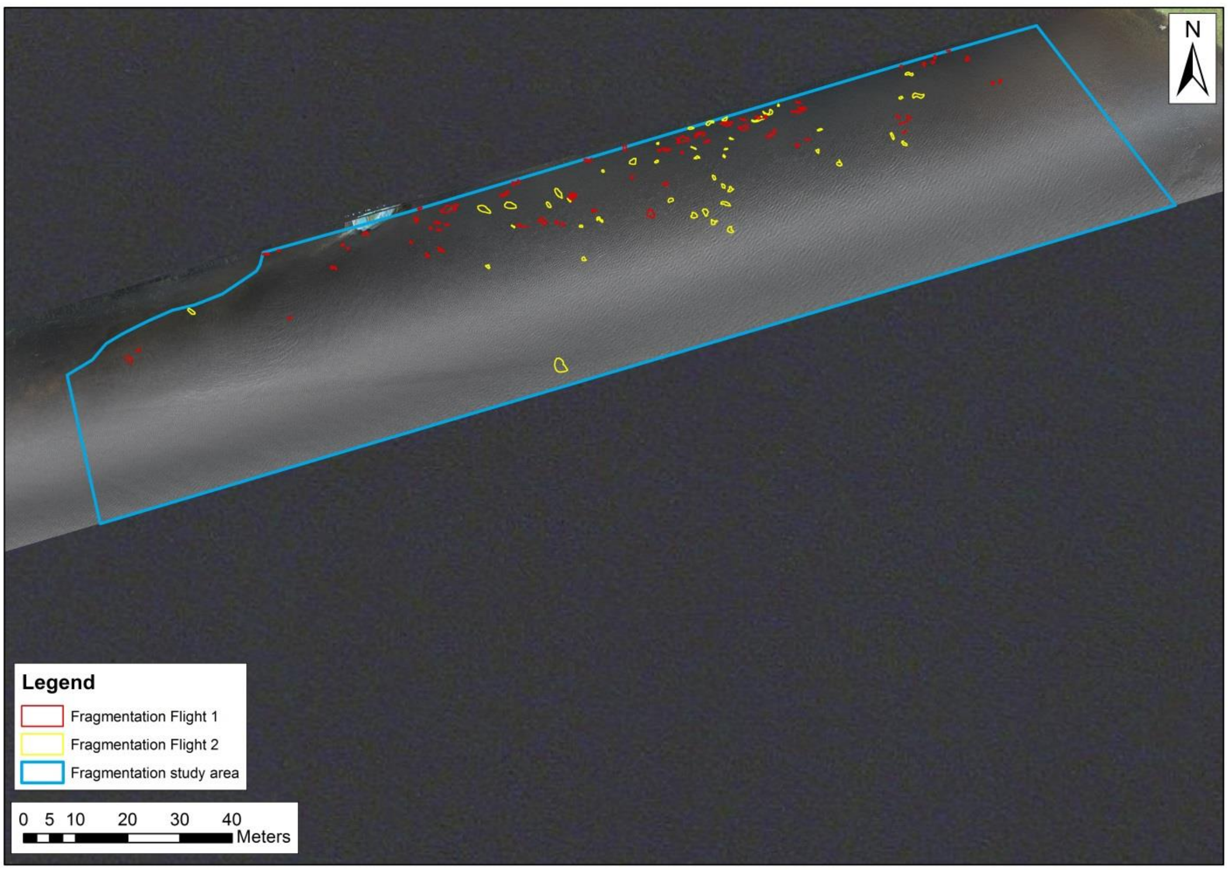

Figure 6.5. Size and distribution of *L. major* fragments recorded during UAV flights 1 and 2.

6.3.3 Cut Quality

The blades appeared to provide a clean cut (black circles in Plate 6.2). It was clear from the underwater footage, taken 21 days after cutting, that re-growth was underway (Plate 6.2). Fresh shoots are clearly visible, growing among cut sections in panels A & B.

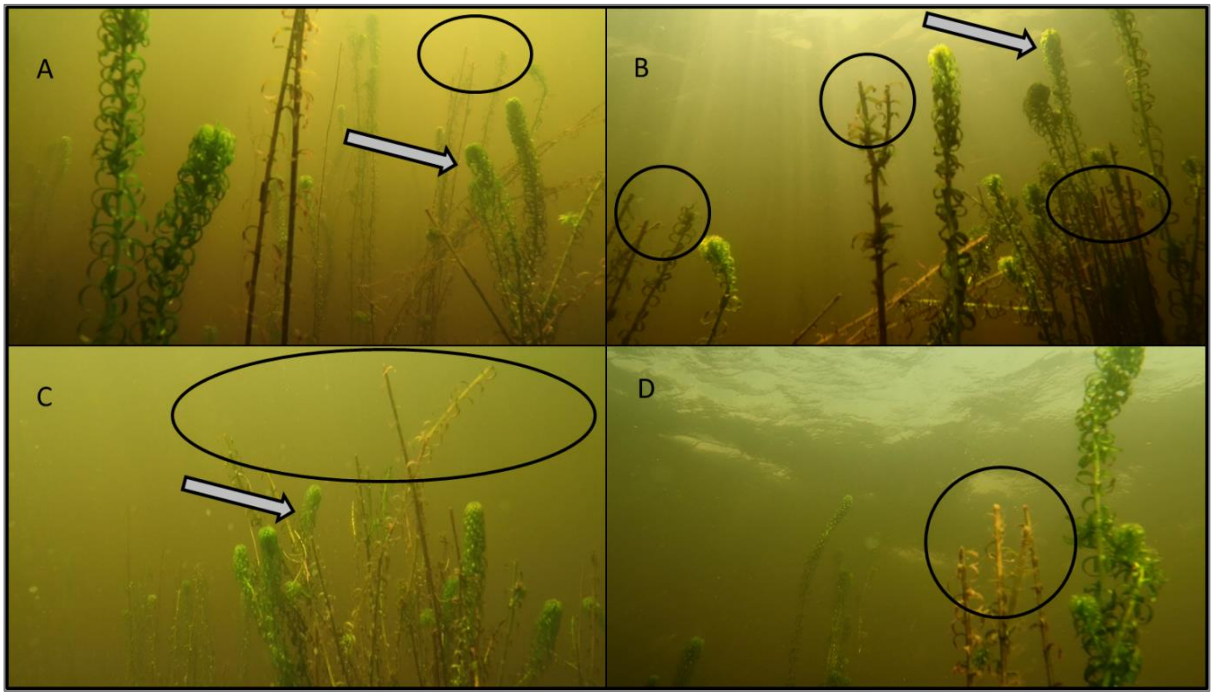

Plate 6.2. *L. major,* post-cutting with the harvester. Images acquired using the ROV. The cut stems are circled in black with re-growth indicated by grey arrows.

6.3.4 Physicochemical Parameters

Turbidity showed notable changes, peaking during cutting but reducing rapidly to pre-cutting levels shortly afterwards (Figure 6.6 and Plate 6.3). Total phosphorous was elevated in the outer and middle bay sites during cutting but levels returned to pre-cutting levels within 21 days (Table 6.4). Chlorophyll *a* levels also increased during cutting and did not return to pre-cut levels at the inner and middle bay sites 21 days post-cutting (Table 6.4).

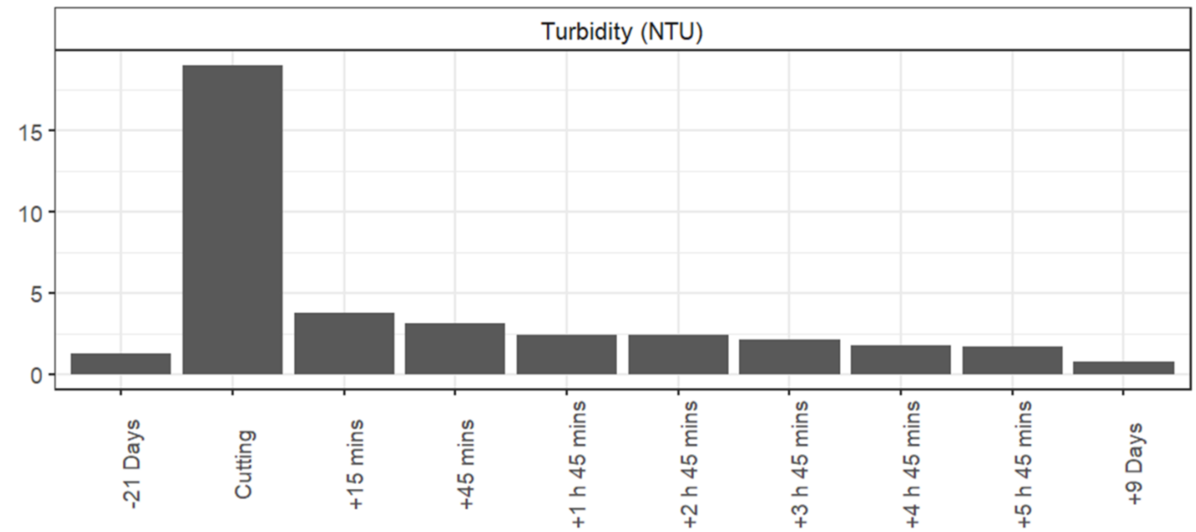

Figure 6.6. Turbidity values recorded at the middle bay site, Drumsnauv Bay.

Plate 6.3. Sediment re-suspension during harvesting, Drumsnauv Bay, June 2019.

Table 6.4. Physicochemical characteristics of sampling sites in Drumsnauv Bay, pre, during and post cutting.

Sampling occasion	Depth (m)	Total N (mg/l)	Ammonium (mg/l)	Nitrite (mg/l)	Nitrate (mg/l)	Total P (mg/l)	Chlorophyll *a* (µg/l)
Inner Bay (Site 2)							
Pre-cut	1.0	<0.5	0.014	<0.005	0.100	<0.05	<1.00
During-cut	1.0	<0.5	0.020	<0.005	<0.1	<0.05	1.34
Post-cut	1.0	<0.5	0.012	<0.005	0.108	<0.05	3.74
Middle Bay (Site 3)							
Pre-cut	1.8	<0.5	0.015	<0.005	<0.1	<0.05	<1.00
During-cut	1.8	<0.5	0.013	<0.005	<0.1	0.21	2.67
Post-cut	1.8	<0.5	0.028	<0.005	0.100	<0.05	2.40
Outer Bay (Site 1)							
Pre-cut	3.0	<0.5	0.010	<0.005	<0.1	<0.05	<1.00
During-cut	3.0	<0.5	0.011	<0.005	<0.1	0.16	2.67
Post-cut	3.0	<0.5	0.013	<0.005	0.105	<0.05	<1.00

6.4 Discussion

In Drumsnauv Bay, the weed harvester rapidly reduced the dense surface canopy of *L. major* stands. This demonstrated the harvester's ability to prepare shallow areas unsuitable for cutting with V-blades, for secondary treatments such as jute matting. This study also found that harvesting can keep the surface clear of *L. major* for at least one month, while considerably reducing surface canopy for up to three months.

However, cutting to a depth of 1.8 m allows incident light to reach the cut plants, stimulating active regrowth (Caffrey *et al.* 2011). Active regrowth was observed in Drumsnauv Bay using ROV imagery 21 days after cutting. *L. major* returned to the surface in the shallowest and earliest cut areas first and appeared to slightly increase its distribution. This, however, is likely due to the fact that the plant was entering its growing season, when regrowth and expansion is expected.

The colonisation ability of a *L. major* fragment is influenced by its size and type (apical tip present) (Heidbüchel *et al.* 2019; Heidbüchel and Hussner 2020). In this study, fragments larger than 2 m^2 were rare but were recorded on both occasions. Fragments of this size would almost certainly contain apical tips, increasing their likelihood of regeneration by a factor of up to 5 (Heidbüchel and Hussner 2020). The size and percentage area of fragment observed in this study show that cutting can pose a risk to the surrounding locations suitable for *L. major* colonisation, unless stringent fragment containment measures are in place. Therefore, harvesting should only be completed during calm weather because wave exposure to partially cut areas can exacerbate fragmentation. To further minimise risk, containment methods should be able to withstand poor weather conditions. To date, containment nets have been used to manage the risk of fragment spread in Lough Corrib. However, such methods can impede boat movement and can fail outright due to excessive wave and wind action. Furthermore, cleaning and maintaining containment nets is time consuming. Bubble curtains are used to prevent the spread of invasive weeds in Lake Tahoe, Nevada (Sierra Ecosystem Associates 2018). This could present a more effective containment solution during harvesting operations in Lough Corrib, particularly where pinch points between bays and the open lake make it practical.

It was expected that poor or partially cut *L. major* stalks would increase the likelihood of fragmentation. ROV imagery showed that the oscillating blades provided a clean cut. Therefore, the observed fragmentation may have been caused by the propeller or occasionally improper adjustments to the blade's speed by the boat's operator. The development of a standard operating procedure setting out best practice for both containment methods and boat drivers would likely result in a reduced fragmentation rate and consequently less risk if containment methods failed.

Aerial imagery showed that cutting caused sediment re-suspension. Re-suspended sediment can act as a source of nutrients, metals and pollutants, leading to reduced water quality and increased primary production (Wang *et al.* 2019). 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*. Correlation between chlorophyll *a* and nutrients such as nitrogen and phosphorous is usually positive when time-lags are considered (Pérez-Ruzafa *et al.* 2019). Therefore, the increase in chlorophyll *a* observed one day after cutting had begun, and one week after it ended should be interpreted with caution. This may indicate that sediment re-suspension became more likely in the shallow areas or was due to an increase in phytoplankton in warmer sheltered areas.

Finally, manual handling issues were improved but not resolved by the harvester. This was because only a few sites were accessible to the harvester for unloading. This resulted in the formation of large mounds that needed to be manually cleared to allow unloading to continue.

In conclusion, the harvester rapidly reduced the volume of weed in a bay that is poorly suited to other control methods. However, in the absence of secondary treatment with jute matting, re-growth will most likely occur again, resulting in canopy formation within three months.

7: Summary and recommendations

IFI continued to support extensive year-round control operations during 2018 and 2019, alongside partner agencies, to reduce the socioeconomic and ecological burden of the invasive plant, *L. major* in Lough Corrib. An average of 123 ha/annum have been treated over the last four years, restoring the amenity value of previously choked-up bays.

An international literature review relating to available control measures supports the current control approach and has revealed no progress in developing eradication measures. The review also identifies potential control methods that are still in development, namely biological control and UVC light. Renewing public awareness initiatives are also identified as potentially useful strategies to prevent further spread.

An investigation into the development of innovative survey techniques found opportunities to improve the accuracy and efficiency of surveys. Results indicate that no single survey method (e.g. UAV, hydroacoustics, satellite, ROV) can be employed across all sites but recommends a combination of methods instead. Furthermore, electronic data collection forms were effective for research and management purposes.

At present, it appears from initial *L. major* distribution mapping in 2018 and 2019 that the annual control efforts undertaken on the lake are slowing the spread of the plant within the lake but will need to be maintained indefinitely to protect the lake from its negative impacts. To date, *L. major* has not been recorded in the lower lake. However, *L. major* continues to slowly extend its distribution towards the lower lake.

Work carried out to date on the effect of habitat and environmental factors on *L. major,* indicates that free CO_2, alkalinity, pH, fetch, substrate, nutrients, temperature, light and depth should be included in statistical models in 2020. A review of the literature also indicates that the availability of free CO_2 may also be an important factor determining *L. major's* atypical season growth pattern in Lough Corrib.

The trial of the weed harvester found that dense canopy cover could be quickly removed, but its benefits were temporary. In addition, the harvester generated *L. major* fragments that can increase the risk of further spread, particularly in the absence of appropriate containment measures.

The next stage of this scientific work will involve;

1. Surveying additional sites (2020) and modelling the influence of habitat and environmental factors on *L. major* in Lough Corrib.
2. Continued distribution mapping of *L. major* to inform the control team of further occurrences.
3. A pilot study to investigate the use of multispectral satellite imagery to map the distribution of *L. major* in Lough Corrib. If successful this element of the project could significantly reduce the number of boat surveys required to map the distribution of *L. major* in the lake to inform management decisions as well as offer additional benefits, including reduced carbon footprint.

Recommendations:

- As the invasive plant is still abundant in certain areas, stakeholder information and biosecurity is still a priority. It is recommended that all information signage be upgraded at existing locations and additional signage be installed, particularly in strategic areas such as Maam and Annaghdown. Consideration should also be given to in-lake signage to highlight problem areas and to remind lake users that there is an on-going problem. This work may also be complemented by use of social media, citizen science sightings app and or websites to remind lake users to exercise caution and use preventative measures.
- All control activities and any new sightings should be recorded in electronic GIS based forms so that information is easily accessible to those managing the lake and *L. major* (for planning and control purposes).
- New survey methods identified during this study should be used for future monitoring and assessments.
- Continue to keep up to date with developments worldwide related to the control and eradication of *L. major*.

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List of key-words 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
HD - High Definition
IAS - Invasive Alien Species
ICHEC - Irish Centre for High-End Computing
ICP-OES- Inductively coupled plasma optical emission spectrometry
IDW - Inverse Distance Weighting
IFI - Inland Fisheries Ireland
LARC - Lagarosiphon Research Lough Corrib
LED - Light-Emitting Diode
NDAVI - Normalized Difference Aquatic Vegetation Index
NGB - Near-infrared Green Blue
NIR - Near-infrared
NTU - Nephelometric Turbidity Unit
RGB - Red Green Blue
ROV - Remotely Operated Vehicle
SAC - Special Area of Conservation
SOP - Standard Operating Procedure
SPA - Special Protection Area
UAV - Unmanned Aerial Vehicle
UVC - Ultraviolet-C

9: Appendices

Appendix 9.1. Field parameters collected in the "LARC" electronic form.

Site Information	Physicochemical *	Quadrat sediment **	Quadrat plant (%)	Grapnel Presence/ Absence	Additional
Date	S_Temperature (°C)	Depth	*L. major*	*L. major*	Grab type
Time	S_Conductivity (µS/cm)	Bedrock	*Chara sp.*	*Chara sp.*	Notes
GPS accuracy (m)	S_pH	Boulder	*E. canadensis*	*E. canadensis*	
Site number	S_Dissolved oxygen (mg/l)	Cobble	*Potamogeton*	*Potamogeton*	
Water depth (m)	B_Temperature (°C)	Gravel	*Myriophyllum*	*Myriophyllum*	
Cloud cover	B_Conductivity (µS/cm)	Pea gravel	Jute		
Wind (Beaufort)	B_pH	Sand			
Wind direction	B_Dissolved oxygen (mg/l)	Mud/silt			
Precipitation	Secchi disk depth (m)	Clay			
		Marl			
		Shells			

*Note: Quadrat data was collected for four quadrats (Q1-Q4) and Grapnel data was collected for three replicates (G1-G3). * Surface values are denoted by S_ and bottom values by B_. ** Boulder (>190 mm), Cobble (65-190 mm), Gravel (11-64 mm), Pea gravel (4-10 mm), Sand (≤3 mm), Mud/silt (≤3 mm).*

Appendix 9.2. Manufacturer, model and accuracy of loggers used in this study.

Sensor	Temperature Accuracy (°C)
HOBO Pendant Temperature/Light 64K Data Logger (UA-002-64)	± 0.53
HOBO Water Temperature Pro v2 Data Logger (U22-001)	±0.21
Reefnet Sensus Ultra Temperature/Depth Sensor	±0.80
TinyTag Aquatic 2 TG-4100 Temperature Sensor	±0.50

Appendix 9.3. Sediment analysis parameters from bay studies.

Macronutrients (mg/kg DW)	Micronutrients (mg/kg DW)	Carbon (% DW)	Physical Parameters (%)
Phosphorus (P)	Iron (Fe)	Total Carbon (TC),	Dry matter @ 105°C
Total Nitrogen (N)	Manganese (Mn)	Total Organic Carbon (TOC)	Organic Dry Mass
Potassium (K)	Zinc (Zn)	Total Inorganic Carbon (TIC)	
Calcium (Ca)	Copper (Cu)	Carbonates	
Magnesium (Mg)	Sodium (Na)		

Appendix 9.4. Dominant sediment type and macrophytes recorded at each sample site in Carrowgarriff.

Sampling date	Site	Substrate	*Callitriche sp.*	*Ceratophyllum demersum*	Charophyte *sp.*	*Elodea canadensis*	*Isoetes sp.*	*Lagarosiphon major*	*Myriophyllum sp.*	*Nitella sp.*	*Potamogeton sp.*	*Utricularia sp.*
21/10/2019	MR1	Silt										
21/10/2019	MR2	Sand						•			•	
21/10/2019	MR3	Silt										
21/10/2019	MR4	Silty mud										
22/10/2019	MR5	Silt										
22/10/2019	MR6	Silt										
25/10/2019	MR9	Silt										
25/10/2019	MR11	Silt										
25/10/2019	MR13	Silt										
22/10/2019	MR15	Silt										
25/10/2019	MR17	Peaty silt										
22/10/2019	MR18	Gravel/Pea gravel/sand										
22/10/2019	MR19	Muddy silt					•	•				
23/10/2019	MR20	Sandy silt										

Appendix 9.5. Sediment type and macrophytes recorded at each sample site in Lackavrea.

Sampling date	Site	Substrate	*Callitriche sp.*	*Ceratophyllum demersum*	Charophyte *sp.*	*Elodea canadensis*	*Isoetes sp.*	*Lagarosiphon major*	*Myriophyllum sp.*	*Nitella sp.*	*Potamogeton sp.*	*Utricularia sp.*
25/10/2019	BT1	Cobble/sand										
25/10/2019	BT3	Silt										
25/10/2019	BT5	Silt										
24/10/2019	BT6	Sandy mud										
25/10/2019	BT7	Silty mud										
24/10/2019	BT9	Clay/silt						•		•		•
24/10/2019	BT11	Cobble/sand					•	•		•		
25/10/2019	BT13	Silty mud										
24/10/2019	BT14	Muddy silt/sand						•				
24/10/2019	BT16	Clay/silt			•		•	•				•
24/10/2019	BT17	Muddy silt/sand						•				
25/10/2019	BT18	Silt										
25/10/2019	BT19	Pea gravel/sand										
24/10/2019	BT20	Cobble/gravel/sand										

Appendix 9.6. Sediment type and macrophytes recorded at each sample site in Annaghdown Bay.

Sampling date	Site	Substrate	*Callitriche sp.*	*Ceratophyllum demersum*	Charophyte sp.	*Elodea canadensis*	*Isoetes sp.*	*Lagarosiphon major*	*Myriophyllum sp.*	*Nitella sp.*	*Potamogeton sp.*	*Utricularia sp.*
30/10/2019	AD1	Marl			•							
30/10/2019	AD2	Marl			•							
30/10/2019	AD3	Marl			•							
30/10/2019	AD4	Marl			•							
29/10/2019	AD5	Marl			•							
30/10/2019	AD6	Marl			•			•	•			
30/10/2019	AD7	Marl			•							
29/10/2019	AD8	Marl	•	•	•	•		•	•			
30/10/2019	AD9	Marl			•							
29/10/2019	AD10	Marl		•	•	•		•	•			
31/10/2019	AD11	Marl			•							
31/10/2019	AD12	Marl			•							
31/10/2019	AD13	Marl			•						•	
31/10/2019	AD14	Marl			•							
29/10/2019	AD15	Marl			•							
29/10/2019	AD16	Marl			•						•	•

Appendix 9.7. Results of sediment analysis in selected bay areas, Lough Corrib 2019.

	Lackavrea					Carrowgarriff					Annaghdown				
Parameter	***BT6***	***BT9****	***BT14****	***BT16****	***BT17****	***MR2****	***MR3***	***MR18***	***MR19****	***MR20***	***AD1***	***AD8****	***AD10****	***AD12***	***AD13***
	Macronutrients (mg/g DW)														
Phosphorus (P)	1.33	1.04	0.81	0.76	0.91	0.36	0.53	0.57	1.06	0.56	0.25	0.88	0.72	0.89	1.11
Total Nitrogen (N)	5.72	2.39	2.84	1.86	2.00	0.39	0.89	0.47	2.91	0.78	7.06	11.60	10.40	14.10	8.71
Potassium (K)	2.44	1.97	2.26	1.78	2.66	0.85	1.03	1.02	1.71	0.98	0.28	0.55	0.86	0.72	0.96
Calcium (Ca)	3.29	3.77	7.23	4.23	4.61	1.52	1.38	2.61	3.82	1.50	360.00	294.00	288.00	255.00	243.00
Magnesium (Mg)	7.98	5.72	6.24	4.98	7.11	4.48	5.70	3.64	7.85	5.38	1.74	1.83	1.62	1.53	1.97
	Micronutrients (mg/g DW)														
Iron (Fe)	69.10	128.00	100.00	146.00	116.00	21.00	28.80	122.00	60.30	28.40	2.55	7.79	5.04	6.83	14.20
Manganese (Mn)	2.05	14.60	24.60	32.40	29.00	0.72	0.86	57.00	1.97	0.74	0.55	0.54	0.22	0.33	1.44
Zinc (Zn)	0.19	0.21	0.20	0.20	0.18	0.05	0.07	0.29	0.15	0.07	0.01	0.03	0.03	0.03	0.04
Copper (Cu)	0.03	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.02	0.01	0.01	0.02	0.02	0.02	0.02
Sodium (Na)	0.18	0.13	0.14	<0.15	0.20	0.06	0.08	<0.15	0.15	0.08	0.20	0.26	0.42	0.30	0.37
	Carbon (% DW)														
Total Carbon	7.8	5.02	4.46	3.69	3.16	0.5	0.97	1.34	3.63	0.98	16.2	18.7	18.2	19	18.2
Total Inorganic Carbon	<1.70	<1.06	<0.95	<0.74	<0.64	<0.11	<0.21	0.41	<0.74	<0.21	11.1	9.69	9.89	9.12	7.58
Total Organic Carbon	7.17	4.47	3.83	3.21	2.71	0.44	1.05	0.93	3.37	0.79	5.09	9.03	8.33	9.87	10.7
Carbonates	3.11	2.7	3.13	2.4	2.26	<0.50	<0.50	2.07	1.33	0.97	55.5	48.4	49.4	45.6	37.9
	Physical Parameters (%)														
Dry matter @ 105°C	18.40	23.40	25.60	27.90	27.80	65.20	58.10	75.4	30.7	57.6	20.00	11.80	11.10	9.19	7.23
Organic Dry Mass	17.80	15.90	13.50	14.20	13.70	2.29	3.09	8.47	10.2	3.08	12.20	21.00	20.00	23.80	24.40

* *Lagarosiphon major* present at the site

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