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Expansion of a localised population of the introduced *Stratiotes aloides* (Hydrocharitaceae) in Lough Derg, Ireland

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Abstract
An expansion of an introduced female clone of *Stratiotes aloides* L. (Water-soldier) was located in a delta region on the western side of Lough Derg, Co Galway (v.c.H15), Ireland in 2007. This population was followed over a thirteen-year period. It was initially located at three adjacent sheltered localities, within sweepback bays on either side of an emerging river and within an adjacent canal. The study involved surface observations later supplemented with aerial images. The shallow water conditions, shelter and the presence of *Phragmites australis* appear to have supported the early establishment by retaining small *S. aloides* clusters amongst its stems. These clusters later merged to produce a mainly surface expanding monoculture. This enlarged from less than 1 ha to approximately 3.3 ha to occupy much of the sheltered Rossmore Bay area during this study. Flowers were first noticed in 2008, and during subsequent visits, producing infertile seed-pods. Expansion took place with the production of daughter plants. A small nearby population, 1 km to the east, within an unused harbour, did not produce an emergent phase. A small group in a shallow cut, between the two locations, disappeared during the study. Aerial images from different sources were useful to identify the expansion of the emergent stage due to the distinctive bright green coloration of surface leaves. It is unclear how this plant arrived in Lough Derg, but might have been a garden plant release. Small drifting plants, seen during wintertime, may yet colonize other regions within this lake.

Keywords: clonal propagation; non-native; aquatic macrophyte; population dynamics; spread.

Introduction
Stratiotes aloides L. (Water-soldier) is a dioecious perennial, the only existing species of its genus within the hydrocharitaceae. It is a relic of the Pliocene (Efremov *et al.,* 2019) and well adapted to winter conditions, when its submerged state can survive below surface ice. It occurs in shallow water bodies with a moderate pH and high dissolved carbon (Prins & de Guia, 1986). This plant has an emergent phase that appears in the spring lasting into the autumn. The young leaves and flowering stalks protrude from rosettes that lie just below the surface. Emergent plants, the only phase that flowers, can form extensive bright-green surface monocultures. The

submerged form has large leaves that seldom appear above the surface in summer (Erixon, 1979; Renman, 1989). Over the winter most of the emergent phase descends below the water surface (Efremov & Sviridenko, 2008). Reproduction is normally from growths of daughter plants evolving from the rosette crown. Sexually reproducing populations are currently unknown in Britain or Ireland (Scannell, 1976; Forbes, 2000).

Stratiotes aloides is native to central and northern Europe and occurs in north-western Asia (Efremov *et al.,* 2019), often forming monospecific stands (de Geus-Kruyt & Segal, 1973). It is present in Europe northwards to 67° N in Finland (Kotilainen, 1954), occurring in shallow environments in canals, ditches, forest waterholes, ox-bow lakes, old river beds and slow-moving waters (Efremov *et al.,* 2019; Toma, 2019). In parts of Europe it has declined in fen ponds (Sarneel *et al.,* 2011) and peaty lakes (Smolders *et al.,* 2003), as it is sensitive to reduced water quality (Sarneel *et al.,* 2011). The habitat it creates is of conservation value for some invertebrates (Suutari *et al.,* 2009; de Vries, 2010), leading to some restoration attempts (Orsenigo *et al.,* 2017) and introductions (Harpenslager *et al.,* 2016). *Stratiotes aloides* has been known in Britain since 1626 (Cook & Urmi-König, 1983) and considered to be native to the Broads region, although previously it was thought to have been more widely spread (Preston & Croft, 1997). There are records from several localities within the Midlands, and elsewhere in southern Britain (Preston *et al.,* 2002) that may have been introduced from garden centres.

The first Irish account was from the Erne Catchment in Co Fermanagh, Northern Ireland. Here it was thought to be native since it has remained in this region for about 200 years (Forbes, 2000) although Preston *et al.* (2002) considers it to be non-native. Reynolds (2002) summarised its presence at five widely dispersed sites. There is an old record from MacKay in 1836 (in Nash, 1993) on the Shannon River upstream of Portumna, and of Lough Derg. It was not seen later at this site, having disappeared by 1866 (Moore & More 1866). Our study was located on the western side of Lough Derg in Co Galway, first recorded in 2007 by Minchin & Boelens (2011) and is more than 15 km downriver from the locality described by MacKay.

This study follows the surface expansion of emergent *S. aloides* over a thirteen-year period by combining ground-truth surveys, satellite imagery, low-level flights by plane and a light drone.

The study area

The main study site of *S. aloides* was on the western side of Lough Derg, south-east Galway (v.c.H15) (Fig. 1). Here the Woodford River drains into the lake at Rossmore Bay. Its delta forms two sweepback shallows to create two bays on either side, referred to in this study as the East and West bays (53.0199 -8.3149) (Fig. 2). This area includes a Canal that opens into the west bay. This Canal was originally intended to hold small craft; but development did not proceed. The Canal, 300 m in length, has a single 6 m wide entrance situated *c.*350 m to the southwest of the entrance of the Woodford River to the lake (Fig. 2). This river is navigable and occasionally dredged, with spoil placed to either side of the navigation channel. The area was not known to have been disturbed during our study.

To the east of Rossmore Bay is a private marina at Kylenashee Harbour *c.*1 km, this consists of an area of *c.*600 m^{-2} (53.0183 -8.2999). Between these two above sites was a seldom-used boat cut leading to a shed (53.0199 -8.3029) (Fig. 1).

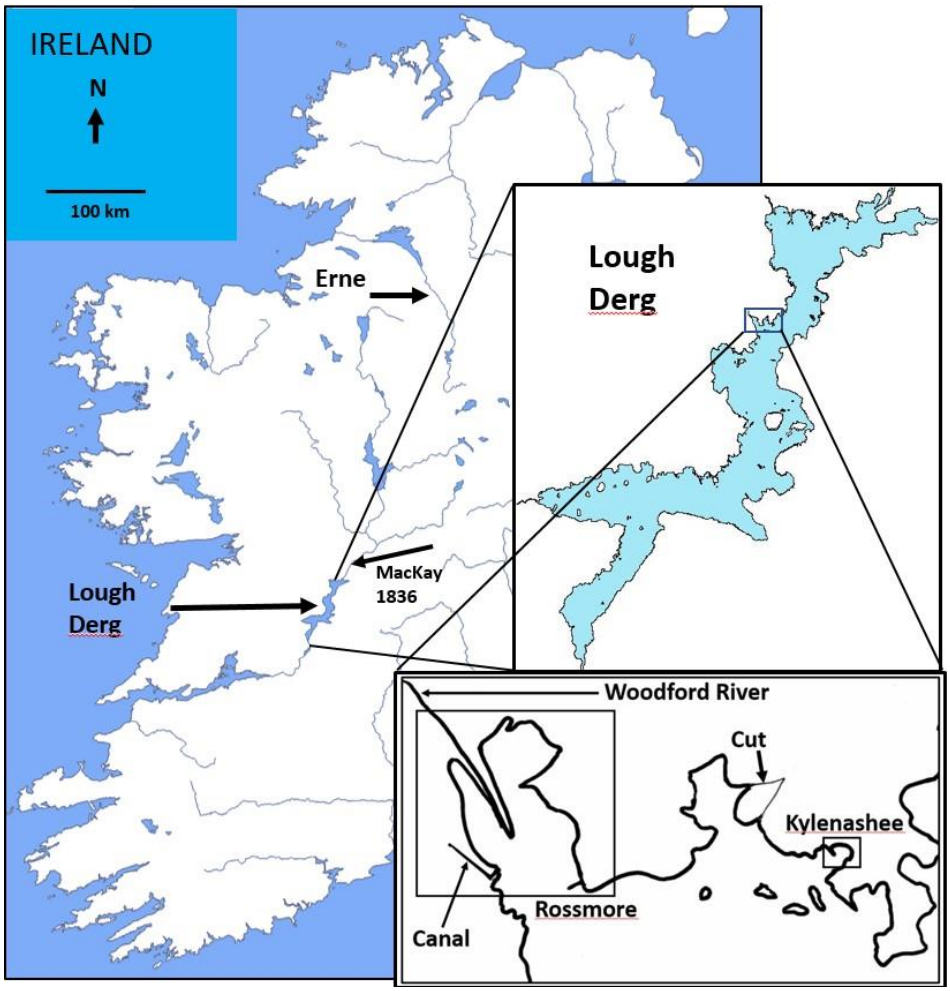

Figure 1. Ireland, Lough Derg (insets) showing the three locations: Rossmore Bay and the Canal, Kylenashee Harbour and the Cut where the study took place. The Upper Lough Erne region is the main site in Ireland for *S. aloides* and MacKay's 1836 record on the Shannon River is shown above Lough Derg.

Methods

Plants were surveyed, using a canoe, in the East and West bays and Canal from September 2007. Photographs and field notes were based on surface observations covering different seasons until September 2015. These observations were then supplemented with selected aerial images of the Rossmore region using Google Earth satellite images for 19 June 2010, 18 August 2015 and for 25 March 2017 using the Geohive national aerial imagery (Ordinance Survey Ireland, 2017). A light drone with GPS was flown providing images for May and September 2019. These combined images showed the extent of the invasive front over time. Direct surface observations and aerial images enabled calculations of the extent of the emergent phase using the Google Earth polygon.

A DJI Mavic Pro Model M1P drone was flown during May and September 2019. Images were taken to cover the Rossmore location using low-level flights to provide seasonal frontal images.

Kylenashee Harbour and the boat cut were visited by canoe during September of 2008 and 2014.

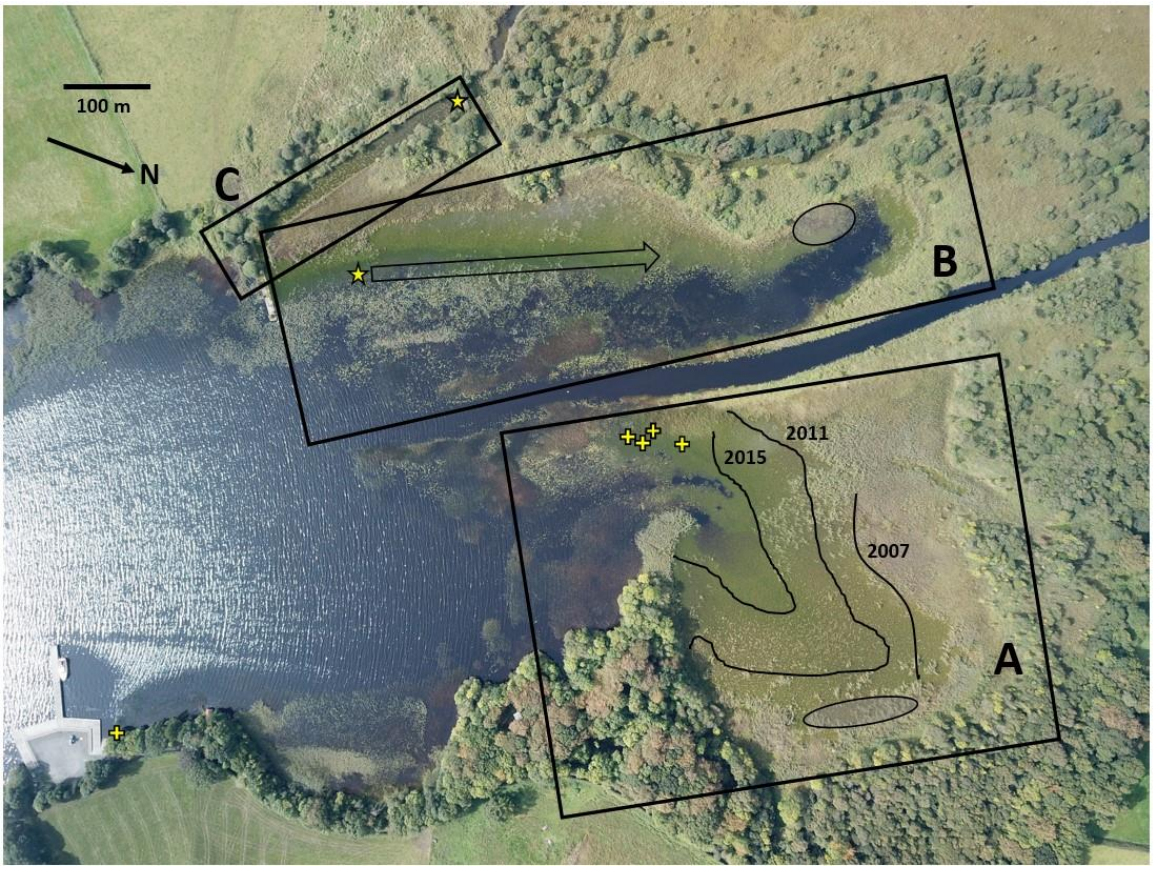

Figure 2. The Rossmore sites, an aerial view during September 2019: A: East Bay with extent of the front progression by years (the 2019 extent is not outlined). February 2015 observations of drift plants (crosses). B: West Bay west of the Woodford River delta. The expansion from the initial clusters (stars) for 2007 is shown for this bay and the Canal (C). The extent of *Hottonia palustris* last seen during 2014 (shaded ovals).

During the summer of 2008, flowers and fruits of *S. aloides* were examined. Common aquatic plants within the study area were identified using Preston & Croft (1997). Conductivity was measured in Rossmore Bay and the Woodford River using a Hanna H199300. Secchi disc measurements were made within Lough Derg to the nearest 10 cm interval.

Results

Aerial and ground truth assessments of emergent plant area

Aerial imagery could clearly distinguish the emergent stage of *S. aloides* on account of the bright green colouration through summer to early autumn of its leaves. The brown to dark-brown submerged plants were not convincingly identified from aerial images, but could be recognised when close to the water surface from a canoe. The

combined colonies in the East and West bays and the Canal expanded during the study to occupy an overall area of *c*.3.3 ha (Fig. 3).

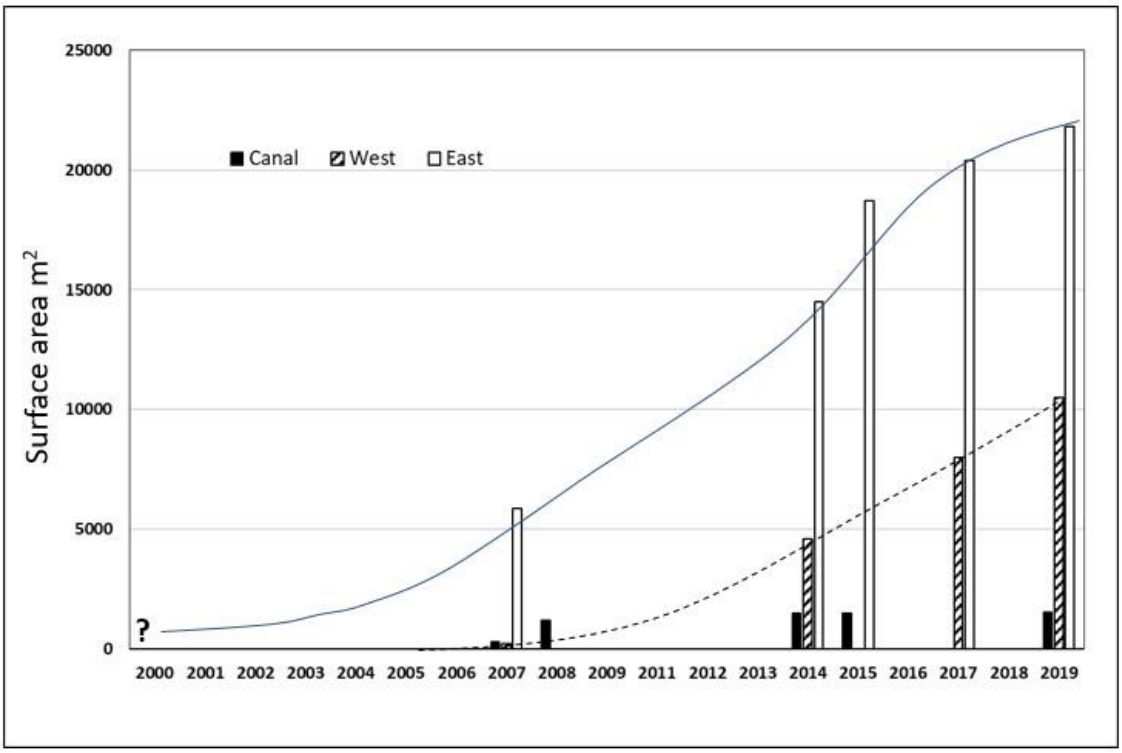

Figure 3. Expansion of *S. aloides* in the Rossmore region showing, East Bay (solid line, with an unknown year of arrival); the West Bay evolving from a small number of plants (dotted) and the Canal (black).

East Rossmore Bay

In September 2007, *S. aloides* covered an estimated surface area of ~5800 m^2. At this time, the invasive front formed a narrow curve about the margin of the inner bay. Submerged *S. aloides* lined the exposed crescent margin with large brown to dark-brown rosettes contrasting with the green of emergent plants. Within the most sheltered part of the bay surface plants were confined amongst stems of the reed *Phragmites australis* (Cav.) Trin. Ex Steud. Submerged plants of *S. aloides* were gradually replaced by the emergent monoculture which spread forwards towards the bay entrance and along the eastern side of this bay (Fig. 2).

In November 2014, and February 2015, few plants were present at the surface. These had large limp dark-brown damaged rosettes and appeared to correspond with grey patches in winter aerial images.

By 2019, *S. aloides* provided an almost continuous monoculture having increased almost four times, since 2007, to occupy most of the available space to depths of one and a half metres over mud. (Fig. 2). During 2019 plants continued to expand along the front from May to September (Fig. 4). The *P. australis* stand, during this expansion, occupied at a lower density, a similar area of *c*.0.7 ha. As the *S. aloides* spread out over the bay surface, other plants that became overshadowed declined or disappeared. Dense clusters of the non-native *Hottonia palustris* L., once observed at depths of 40 to 80 cm, were not recorded after 2014, whereas *Elodea*

nuttallii (Planch.) H. St.John*, Lemna minuta* Kunth and native plants *Potomogeton natans* L., *Hydrocharis morsus-ranae* L., *Oenanthe aquatica* (L.) Poir. were reduced in abundance. *Nuphar lutea* (L.) Sm. and *P. natans* became crowded and co-existed with submerged *S. aloides,* beyond the emergent front.

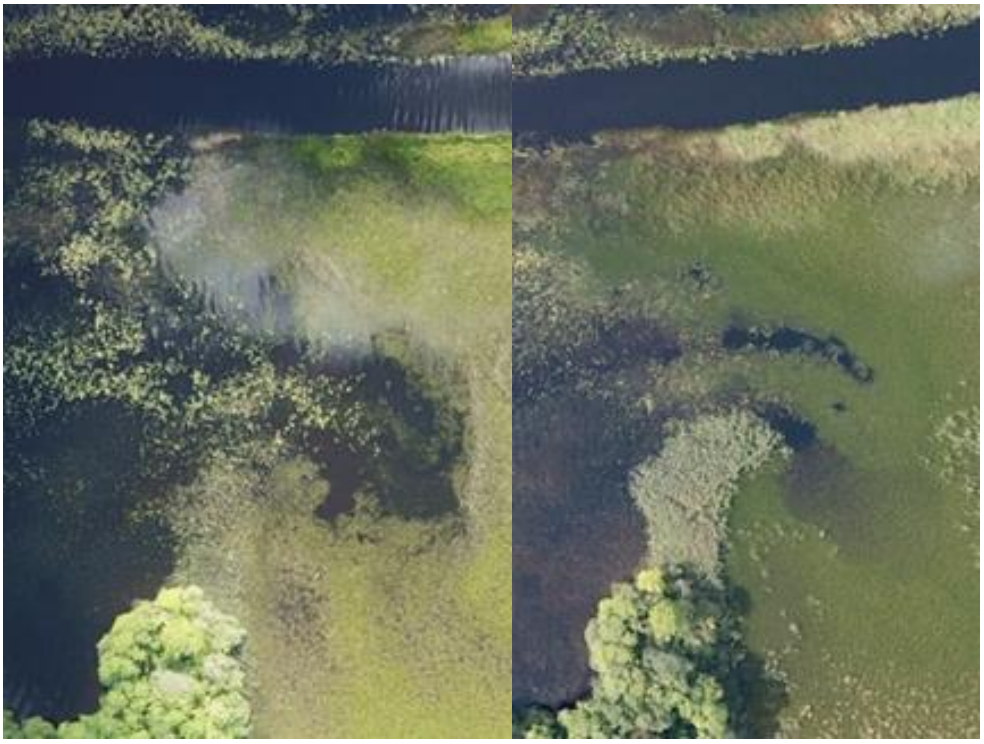

Figure 4. Aerial images of East Bay from May (left) and September (right) showing frontal expansion during 2019.

Female flowers were recorded from June to September 2008 at a density of *c.* 1 m^{-2}, with pods appearing from July to subsequently attain a density of *c.*3 m^{-2} by September. Leaf growth from the rosette crown displaced seedpods to later lie beneath the crown by autumn. Asexual reproduction was evident in emergent and submergent plants. Buds from the central region of the rosette developed into daughter plants from April (Fig. 5a). Subsurface plants ranged from brown to dark brown (Fig. 5b and c).
Small detached, rootless, and isolated *S. aloides,* were seen entrapped within the marginal stand, of the previous year's *P. australis* dried-out stems, during February 2015 (Fig. 5d). These were found isolated and beyond the emergent front. At the same time a small plant was found stranded on a shore 200 m beyond the nearest plants beside a quay (Fig 2).

West Rossmore Bay
In September 2007 only single emergent and submergent plants were encountered between reed stems within an area of < 50 m^{-2} adjacent to the Canal entrance (Fig. 2). These, in the following year, produced clusters over a greater area within the *P. australis* stand.

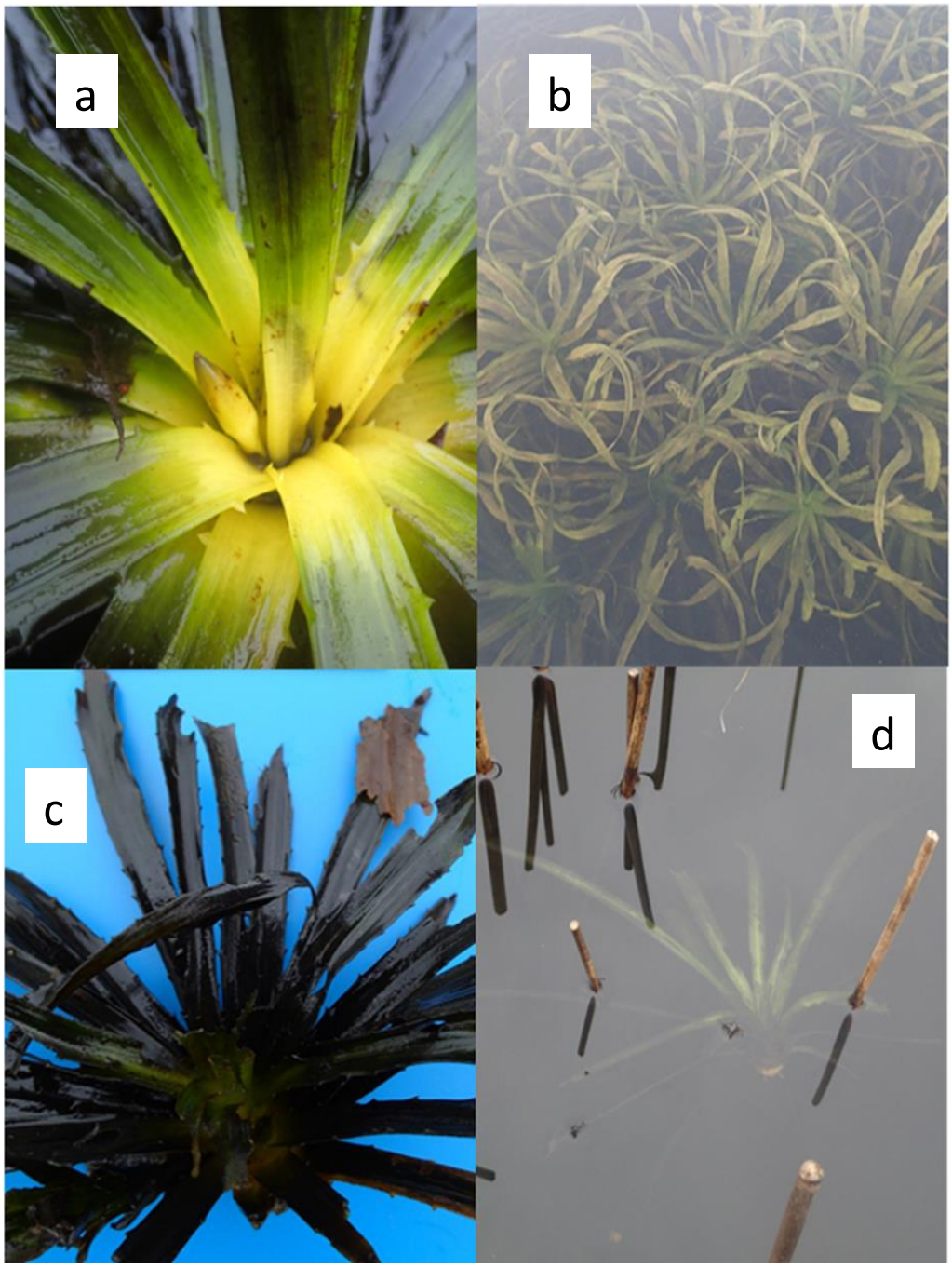

Figure 5. (a): daughter plant buds being produced from a crown during the emergent stage. (b): sub-surface plants in summer. (c): subsurface plants in early spring showing early development of buds. (d): drift plant within broken reeds during February 2015.

In 2014, there were surface observations of fifty-eight separate clusters of emergent plants. These occupied areas between <1 m^{-2} to 10 m^{-2} within reeds; and in open spaces among the reeds, monocultures of up to *c.*400 m^{-2} were present. In the shallower water between the reeds and the shore was an elongated stand approximately 3 m to 10 m in width, extending half-way into the bay from the Canal

entrance along the shore (Fig. 2). At the innermost part of this bay were two narrow bands of *S. aloides* of approximately 40 m in length, with single plants seen in between. Reeds in this bay occupied a total area *c.*1.2 ha.

In 2015, there was a further co-joining of clusters within the reeds and an additional extension to the band occurring along the shore which extended further through the reeds and across spaces between them, spreading to the end of the bay. A narrow band of *S. aloides* had, by this time, formed a new group on the eastern side of the West Bay alongside the dredge-spoil of the Woodford River. In addition, a new group appeared at the end of the delta, close to where the river entered Lough Derg. The expansion within the bay continued, so that by September 2019 the estimated surface cover had increased to 1.05 ha.

A shallow water concentration of *Hottonia palustris,* that occupied an estimated area of 600m^2 within the shallows of the bay, was no longer seen after 2014, following the extended cover by *S. aloides.* There were declines of other native plants where *S. aloides* had become dominant. *Elodea nuttallii,* noted in 2007, was no longer seen.

The Canal

In September 2007, <10% of the Canal area was covered with emergent *S. aloides* at its innermost end adjacent to small stands of *Typha latifolia* L. and *Shoenoplectus lacustris* (L.) Palla. Large brown rosettes of submergent *S. aloides,* with diameters of 60 to 150 cm, formed small groups close to the surface occupying an area of <25% throughout the Canal. In July 2008 the emergent stage occupied approximately 40% of the surface area and by the summer of 2010, the entire surface was covered with leaves of rosettes facing diagonally upwards; small open spaces between plants. Any submerged rosettes could not be seen.

Flowers were first recorded in the Canal during June 2010. Over the following years the surface became dominated by *S. aloides* with reduced numbers present at the surface overwinter (Fig. 6). By September 2014 plants at the surface were sufficiently abundant that protruding leaves of adjacent plants overlapped. This crowding extended towards the Canal entrance with plants sufficiently packed to become purged into the West Bay region. In 2014, small numbers of submergent plants accumulated on the exposed southern side of the slipway at the Canal, and remained here in 2019. The surface expansion in the Canal over thirteen years was from about 100 m^2 to cover the entire canal of 1500 m^2.

In April 2011, there was a seasonal decline to <40% cover. In November 2014, only large rosettes of separated large brown plants were close to, or at, the surface and these were devoid of the distinctive green colour. In February 2015, fewer dark brown plants remained at the surface appearing in loose clusters with decaying ragged leaf straps which were easily snapped from their subsurface crowns. Some of these had cord-like roots to >1.5 m in length.

The Harbour and the cut sites

The plants at Kylenashee Harbour were all submerged or just at the surface during the summer visits in July 2008 and June 2015 and were not examined overwinter. Satellite and plane images did not reveal any clear indication of the presence of this plant from any of the time periods available. The drone was not flown in this region. The six plants in the shallow cut in July 2008 were not subsequently seen during June 2015.

Figure 6. The Canal views (above) 3 September 2007 and 17 September 2014, (below) 25 November 2014 and 11 February 2015.

Environmental parameters

In Lough Derg the lower water transparency is in part due to the run- off of humic acids from peatlands providing Secchi disc readings varying seasonally with maximum levels of 2.9 m since 2010. Temperatures within this bay occasionally are sufficiently low to enable short periods of ice cover to form. One period in November 2010 resulted in some weeks of ice cover, a time when a large part of the lake had a cover of ice. Summer temperatures in shallows elsewhere in Lough Derg attained 23.4° C during June 2016. The conductivity levels on the western side of Lough Derg are generally lower with measurements made in the Rossmore delta and Woodford River ranging from 132 to 142 whereas on the eastern side of Lough Derg the values are usually above 400.

Discussion

It was possible to follow the expansion of *S. aloides* using historical aerial images due to the distinctive colour of emergent plants. The submergent phase, while also extensive, was not recognisable from aerial images due to their dark brown colouration and due to the low water transparency of the lake water from peatland runoff. Nevertheless, individual plants close to the surface, could be recognised from direct observation and drone images. Aerial images for evaluating the status of aquatic plants have long been used (Andrews *et al.,* 1984; Schloesser *et al.,* 1988; Marshall & Lee, 1994). More recently, a drone with a multi-spectral camera was used

to measure the expanse of both the emergent and submerged stages of an invasive population of *S. aloides* in Canada (Chabot *et al.*, 2018). The drone we used did nothave this capability. As available satellite images increase in resolution, the opportunity of using historical images may become more useful for general monitoring of some aquatic plants.

There was already an established population with a distinctive emergent stage within the East Bay and the Canal when first examined during September 2007. The overall expansion of the emergent population within the Rossmore Bay and the Canal grew from *c.*0.6 ha in 2007 to *c.*3.3 ha in 2019 (Fig. 3). The sheltered environment within this bay would appear to be important for the establishment and expansion of *S. aloides*. The stems of *P. australis,* in the shallower water, may have greatly contributed to the initial stages of colonisation by providing a baffle with the capability of retaining drifting plants. Entrapped individuals, amongst reed stems, expanded to form clusters with continued growth. These ultimately formed a monoculture and extended beyond the reed margin. Water levels in Lough Derg are legally maintained to within 61 cm (Anon, 1934); and so, plants in the lake remain immersed in water throughout the year and may be a further feature sustaining the population. The water level regulation followed the construction of a reservoir serving a hydroelectric power station, and has been in operation since 1929. Before construction, water levels in the lake in 1836 ranged over 203 cm (Shannon Commissioners, 1837). According to Wang *et al.,* 2016 water levels can have an impact on plant production.

The initial appearance of *S. aloides* in the West Bay seen in 2007 may have evolved either from some plants from the Canal, the East Bay or perhaps from Kylenashee Harbour. Nevertheless, by 2014, following the rapid expansion of the population in the Canal, plants had become sufficiently abundant to be purged through the entrance to the Canal into the West Bay. In this, and subsequent years, there was a 'calving' at the Canal entrance with releases into the lake. Most of these released plants will have been carried into the reeds in the West Bay by the effects of wind. This growth within the West Bay will have evolved from a small number of plants near the Canal entrance to extend within the Bay and towards the Woodford River delta.

In Rossmore Bay there was a distinct seasonal pattern to the surface appearance *S. aloides.* There was a profuse emergence in May, and throughout the summer, to September/October when most plants submerge. Not all plants descended during winter. Those remaining appeared as indistinct patches in a March satellite image. This appearance corresponded with February and March observations of old plants close to the water surface. Submergence is an adaption for cold environments with seasonal surface ice (Efremov *et al.,* 2019). In Ireland, remnant reed stems protrude and persist above the water surface over winter and into the following year. In Lough Derg, since 2000, there were only occasional short periods of surface ice that may have resulted in breakage to reed stems with the possible release of plants.

In Kylenashee Harbour, emergent plants did not appear during the visits made in summer. It is not clear why; but might be due to the deeper water of > 2 m and lower water clarity at this site. The Kylenashee Harbour population remained submergent and did not show any clear indication of expansion during visits over a nine-year duration, despite the sheltered conditions. Kornatowski (1979) noted such

an absence of the more productive emergent plants in a Polish population.

All flowers examined were female. This is consistent with the populations recorded in Northern Ireland (Forbes, 2000) and Britain (Stace, 1997). Seeds, while produced, were parthenocarpic and so the expansion in Lough Derg is from the asexual production of daughter plants from rosette crowns. Since viable seeds are not produced in Ireland (Scannell, 1976) there is no natural long-range dispersal; consequently, Lough Derg plants must have evolved from an introduction of a seminal clone (Preston & Croft, 1997). This is not unexpected since according to Smolders *et al*. (1995) viable seed production seldom takes place north of a line from Cherbourg to Leningrad (Cook & Urmi-König, 1983). The population in Lough Derg may have originated from a planting from a garden centre; perhaps this was an introduction to Kylenashee Harbour than to the more remote Rossmore Bay. Such an event may also have given rise to the temporary plants in the shallow cut between these areas. The source is unlikely to have come from the Woodford River, or from its associated drains and ditches, as no *S. aloides* plants were found within a distance of 2.6 km. Furthermore, it is unlikely plants evolved from MacKay's record from the Shannon River some 150 years earlier, since Moore & More (1866) did not subsequently find this population, and there have been no records since. We found individual plants dispersed and separated from the main population and either entrapped within reed stems during the winter or stranded on a shore. Clearly plants can become dispersed into the open lake, aided by wind-induced surface water currents, that could result in further populations appearing elsewhere in the lake at some future time. Snyder *et al.* (2016) have stated the importance of its spread with water currents.

Conditions in Ireland cannot always have been suitable for *S. aloides* as populations expire from time to time (Colgan & Scully, 1898; Reynolds, 2002; Forbes, 2000). This would appear to be the case of the small group of plants in the shallow cut. However, some populations have existed for a considerable period of time. In Co Fermanagh (v.c.H33) it has been present for over 200 years forming similar dense emergent populations (Forbes, 2000), to what will have evolved in Rossmore Bay. In the Netherlands and the Broads region of Britain it can also produce dense emergent stands (Smolders *et al*., 2003; Preston & Croft, 1997). Elsewhere in Europe there have been local declines considered to have been due to either eutrophication, lowering of the water table through drainage or competition from lemnids (Smolders *et al.,* 2003).

The emergent expansion of *S. aloides* will have overgrown other aquatic plants; but did not appear to have reduced the extent of the *P. australis*. Two small populations of *H. palustris,* one in each of the bays, occurring in water < 1m, were no longer seen. Other plants gradually declined with the expansion of the emergent front over time. This surface dominance and crowding at the surface most probably outcompeted other plants for light and space, as was found by Forbes (2000).

Conclusion

Using combinations of satellite, plane and drone imagery, supplemented with direct surface observations, it was possible to follow the expansion of an emergent female clone of *S. aloides* over a thirteen-year period in an Irish lake. This expansion took place in a shallow bay most probably aided by the presence of *P. australis* where drifting plants became entrapped between reed stems throughout the year, and also

aided by a low annual surface water range. Plants multiplied to produce an emergent carpet that expanded from less than a hectare by more than five times. Submerged plants were not quantified although these preceded the presence of the emergent expansion. Apart from the reeds, other aquatic plants declined with the emergent surface growth. Another nearby population of *S. aloides* failed to produce an emergent carpet during this study and a small separate cluster of plants at a further location disappeared.

Acknowledgements
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