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GUIDANCE AND RESOURCES FOR ACCURATE AND CONSISTENT USE OF THE LEVEL OF FOULING (LOF) METHOD

GUIDANCE AND RESOURCES FOR ACCURATE AND CONSISTENT USE OF THE LEVEL OF FOULING (LOF) METHOD

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EXECUTIVE SUMMARY

Boat biofouling is a prolific and consequential vector of marine non-indigenous species (NIS) and pests. The prevalence of NIS in marinas worldwide and the occurrence of extensive and diverse biofouling communities on transient boats underscore the high propagule and invasion pressure that routinely occurs when this pathway is unmanaged. Biosecurity policies designed to reduce movements of biofouling with boats rely on robust and efficient methods to support management action that reduces pest species establishment and spread. This includes rapid evaluations of biofouling on vessel hulls to inform compliance decisions or to determine if management standards are effective. The 'level of fouling' (LOF) scale developed by Floerl et al. (2005) for describing and quantifying biofouling assemblages on vessels is used increasingly in Aotearoa New Zealand for these purposes. This report describes new guidance and resources to support correct and consistent application of LOF methods by current and future practitioners to enhance boat biofouling pathway management across a range of implementation scenarios.

Guidance and operational tools have been developed for recreational vessel biofouling inspections using the LOF rank scale. An extensive archive of underwater still and video imagery on the biofouling status of >100 yachts and motorboats has been developed and used to populate training materials that promote accuracy and precision among practitioners. Quantitative and validated biofouling percentage cover of images is included in an electronic application that can be used for training and self-evaluation. Operational protocols for implementing the LOF method have been clearly articulated for current and future practitioners with guidelines and tips for avoiding pitfalls of misallocating LOF ranks. A new LOF calculator also offers a standardised approach to LOF data recording and whole-boat LOF calculations based on multiple LOF ranks from various hull and niche areas of boats. A workshop on this topic, attended by a wide array of Aotearoa New Zealand's LOF practitioners, provided additional discussion and feedback for newly developed guidance and future directions. Retaining the ease and efficiency of the LOF method while understanding and enhancing accuracy and consistency of application will underpin policies to reduce biofouling-mediated introductions. Ultimately, the LOF method has strong potential to contribute to effective pathway management for boat biofouling in Aotearoa New Zealand and overseas that reduces the risk of marine NIS and pest proliferation of our coastlines.

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1. INTRODUCTION

Boat biofouling is an important anthropogenic transfer mechanism for marine species and a cause of marine invasions worldwide (Minchin et al. 2006). Studies conducted across a wide range of global regions highlight the occurrence of biofouling on boats, including non-indigenous species (NIS), and regular transits of large populations of boats as drivers of invasion risk (Clarke Murray et al. 2011; Ulman et al. 2019; Ashton et al. 2022). Studies also highlight the occurrence of NIS in marinas as focal points for NIS establishment (Ruiz et al. 2009; Foster et al. 2016). Boats contribute to both primary introductions of NIS after long-distance transits (Floerl et al. 2008) and secondary spread of NIS among marinas that expand the distributions of NIS within their invaded ranges (Floerl & Inglis 2005; Peters et al. 2019; Ashton et al. 2022). Boats provide a link between hubs of shipping activity, and the associated marine NIS and pest populations at commercial ports, with bays and estuaries that are not visited by large ships (Davidson et al 2010; Zabin et al. 2014). Similar risks occur with recreational boats as vectors of NIS spread in freshwater systems, both overland as trailered boats (Johnson et al. 2001; Rothlisberger et al 2010; Cole et al. 2019) and via in-water transport (Kelly et al. 2013). In marine systems, boat biofouling contributes to invasion pressure in marine protected areas (MPAs) that compromises the conservation and ecosystem function goals of these valued ecosystems (Cunningham et al. 2019; Iacarella et al. 2019; Iacarella et al. 2020). As a result, boats have come under increasing scrutiny over the last 15 years for their consequential role in NIS transport.

Examples of biofouling and NIS occurrence on transient boats underscores the prevalence of the vector as a driver of invasion risk. Ulman et al. (2019) reported 71% of 600 boats sampled in the Mediterranean had NIS in their biofouling communities in a region with an estimated 1.5 million boats. In Alaska, 62% of boats had biofouling after transits of >900 km, including several NIS (Ashton et al. 2014). Transient boats sampled in California, where 300,000 recreational boats are registered in coastal counties, recorded 158 taxa from 49 boats, some of which had extensively high biofouling abundance estimated at 10^6 organisms (Ashton et al. 2022). In Aotearoa New Zealand, a large study of 182 yachts arriving from overseas showed that 82% had biofouling comprised of 202 taxa, with 75 species non-native to Aotearoa New Zealand, 45 of which were not known to be established in the country at the time (Floerl et al. 2008). These findings highlight the potency of boat biofouling for providing invasion opportunity to marine NIS and a need for effective management to curtail boat-mediated NIS spread (Clarke Murray et al. 2011).

Biosecurity policies designed to reduce movements of biofouling with boats rely on robust and efficient methods to support management action that reduces pest species establishment and spread. This includes rapid evaluations of biofouling on vessel hulls to inform compliance decisions or to determine if management standards are effective. The ‘level of fouling’ (LOF) scale developed by Floerl et al. (2005) for describing and quantifying biofouling assemblages on vessels is used increasingly in Aotearoa New Zealand for these purposes. This report describes new guidance and resources to support correct and consistent application of LOF methods by current and future practitioners to enhance boat biofouling pathway management across a range of implementation scenarios.

1.1. The level of fouling (LOF) scale: origin, past and present use

The LOF scale described by Floerl et al. (2005) was originally devised as a means of quantifying biofouling on international yachts arriving in Aotearoa New Zealand. It was intended as a tool that border authorities could apply via above-water inspection, with LOF ranks corresponding to biofouling levels present on submerged parts of vessels' hulls. Calibration exercises undertaken for 189 recreational vessels indicated moderate agreement between above-water LOF ranks and diver- or hull-cam-based quantitative surveys of biofouling. Above-water LOFs correctly identified 60% of vessels that had biofouling and found some degree of correspondence between LOF ranks and actual biofouling extent. However, the method returned incorrect predictions for biofouling presence for 40% of vessels (Floerl et al. 2005). When used for recreational vessel biofouling assessments around the USA and Canada, correspondence between surface-based LOFs and actual biofouling intensity was not deemed sufficient to qualify the method as a rapid assessment tool (Clarke Murray et al 2013; Zabin et al. 2014).

Nonetheless, there was agreement among early adopters of the LOF scale that it provided an efficient and intuitive tool for direct categorisation of biofouling abundance on vessel hulls. If applied correctly, the LOF scale is highly cost-effective relative to traditional and time-consuming quantification methods, such as the use of sampling quadrats, point counts, and image-based percentage cover analyses. While the original intention of LOF ranks (to serve as a surface-based predictor of underwater biofouling) has largely been dropped, the LOF scale has been widely and successfully used for *in situ* quantification of biofouling abundance on recreational and commercial vessels in Aotearoa New Zealand (Hopkins & Forrest 2010; Inglis et al. 2010; Brine et al. 2013; Forrest 2014, 2016; Forrest 2017).

Over the past years, the LOF rank scale has also become incorporated into regulatory documents and other standards that have been developed or proposed in Aotearoa New Zealand's regions and nationwide. Examples of this include:

i. Marine biosecurity regional pathway management plan requirements developed under the Biosecurity Act 1993 by Northland Regional Council;
ii. Biofouling rules developed under the Resource Management Act 1991 by Auckland Council for the Auckland Unitary Plan;
iii. Conditions on vessel swing mooring consents being developed by Tasman District Council;
iv. Conditions on marina berth agreements developed for Nelson Marina by Nelson City Council, which are linked to revisions of Regional Pest Management Plans;
v. Regional Coastal Plan: Kermadec and Subantarctic Islands (Department of Conservation 2017);

vi. Conditions required for formal testing of in-water cleaning and capture (IWCC) systems in Aotearoa New Zealand and abroad; and
vii. The Clean Hull Plan that is being developed by the Top of the North Marine Biosecurity Partnership.

In association with the above initiatives, and / or as part of regional pathway management programmes, several jurisdictions (e.g. Northland, Auckland, Bay of Plenty, Marlborough, Nelson, and Tasman regions) have established operational dive and snorkelling teams that quantify biofouling abundance on hundreds to thousands of vessels annually, using the LOF scale.

1.2. Use of the LOF scale for marine pathway management: critical issues

It is important for the success and credibility of pathway management initiatives that they are based on sound methods, and sound implementation of these methods. Incorrect or inconsistent use of the LOF method can undermine the robustness and evenness of application among locations, and possibly affect public perception of vessel screening programmes. In recent years, there has been some variation in the way vessels are scored with LOF ranks during regional surveillance initiatives. Some teams allocate a single 'whole-vessel' LOF rank following inspection, while others record multiple LOF ranks associated with different hull and niche areas, and then aggregate these ranks into a whole-vessel estimate. While snorkel- or diver-based assessments are used most commonly, several jurisdictions have purchased remotely operated vehicles (ROVs) and / or are trialling the use of surface-operated 'pole-cams'. Whatever approach is used, it is important to ensure that it results in consistent allocations of accurate LOF ranks.

Until recently and despite 17 years of use of the LOF scale, the only existing guidance was a short document developed for MAF-BNZ (now Biosecurity New Zealand MPI) to support a vessel sampling programme in 2005–07 (Floerl 2004). While useful, that document is limited in the amount of practical guidance it provides, and it does not cover strategies that enhance accurate and consistent scoring, and that minimise 'observer bias' among personnel undertaking LOF assessments.

There is a need for detailed guidance and protocols around LOF rank allocation, and for rigorous tools that enable the calculation of whole-vessel LOFs from multiple niche LOFs, in particular if the biofouling status determined by surveillance initiatives can have consequences for vessel owners and operators. In essence, the LOF scale is analogous to the modified McLean rank scale for rabbit infestation, both in its structure / definitions and in the context of its application (Lough 2009). The McLean scale comprises eight nominal ranks (Appendix 2) and is used to estimate rabbit densities on private and public land around Aotearoa New Zealand based on the density of faecal pellet 'heaps'. Regional Pest Management Strategies throughout Aotearoa New Zealand require landowners to undertake rabbit control programmes where McLean ranks exceed a critical threshold set by the council. To ensure robust application of the scale, compliance and trend monitoring is undertaken using protocols developed by the National Pest Control Agencies (NPCA 2020). Training and skills maintenance for McLean scale 'practitioners' is important to enable implementation of robust rabbit monitoring and control programmes (Lough 2009). The same applies to the use of the LOF rank scale when it is applied for marine biosecurity pathway management initiatives, which is a priority for domestic pathway management in Aotearoa New Zealand.

2. PROJECT OBJECTIVES

This report covers **Part B** of the overall LOF guidance and resource development project. Part A was carried out in 2020/21 and resulted in the following outputs (Davidson et al. 2021):

1. **Refinement of the LOF rank definitions.** The critical percentage cover element of the scale was retained but potentially confounding or confusing aspects related to species richness and composition were removed.
2. **Collection of high-quality imagery.** Cawthron divers inspected >100 recreational boats (sailing yachts and motor launches) and produced an archive of more than 1,500 images and videos of submerged hull surfaces and niche areas with varying biofouling extent encompassing the full range of LOF ranks.

The objective of **Part B** of the overall project was to build on the outputs of Part A and incorporate them into training and operational resources for LOF-based hull surveys:

1. **Step-by-step protocols** for applying the LOF system across all scenarios in which LOF measures are applied (diver and ROV in-water and above-water scenarios).
2. **Morphometric analysis** of boat wetted surface area (WSA) and the contribution of niche areas to overall WSA. **Development of a 'LOF calculator'** that aggregates individual LOFs from multiple hull and niche areas of a vessel into a single whole-vessel LOF rank using appropriate weightings.
3. **A guidance manual** outlining recommendations and methods for observer training to ensure robust and consistent application of the LOF rank scale within and between regional teams.
4. **A software application (app)** tool for operational use that incorporates the resources listed above and that can serve as a training, calculating, decision, and quality assurance tool for regulators and biosecurity practitioners.
5. **A training workshop** with LOF scale practitioners to: (i) revisit the LOF scale and its definitions and discuss the modifications applied during this project; (ii) measure and discuss observer accuracy and precision of LOF use, and (iii) showcase the resources developed during this project (in particular the LOF calculator and a prototype app) and gather feedback and suggestions from workshop attendants that can feed into the finalisation of these resources (Appendix 1).

3. LEVEL OF FOULING CATEGORIES

The LOF scale was developed by Floerl et al. (2005) as a series of six categories that were defined based on percentage cover and taxonomic richness of biofouling (Figure 1). The categories do not have equal ranges with respect to percentage cover of biofouling. They are unevenly distributed, from zero macroscopic biofouling with and without biofilms (LOF 0 and LOF 1); presence of macrofouling to 5% cover (LOF 2); 6% to 15% cover (LOF 3); 16% to 40% cover (LOF 4); and 41% to 100% cover (LOF 5).

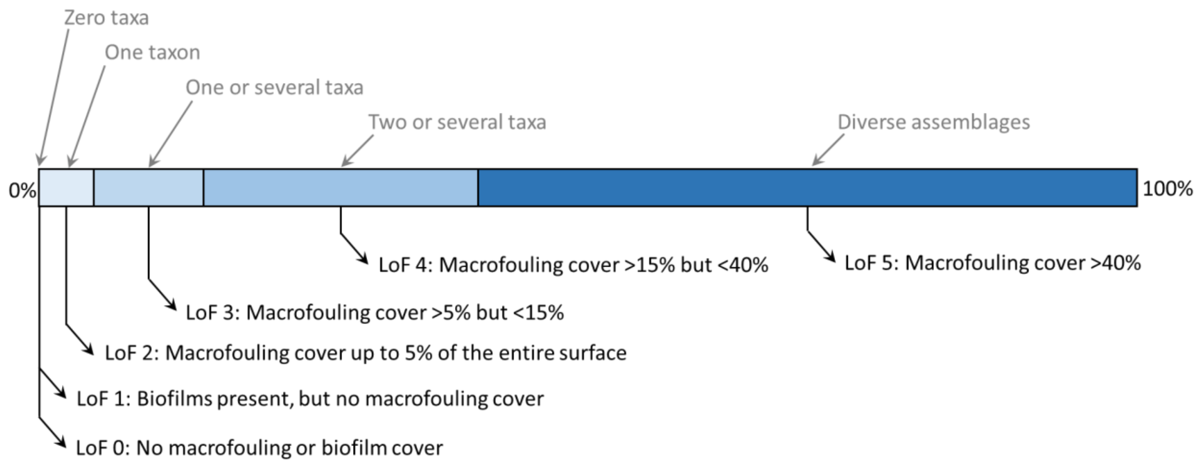


Figure 1. The LOF scale has six categories that were originally defined using a combination of percentage cover of biofouling on boats and probable taxonomic richness that correspond with these percentage cover (extent) values. In this updated guidance, primacy is given to the percentage cover criteria.

Using a categorical scale makes it easier to be consistently accurate without using specific quantitative levels of percentage cover. The approach does not require sampling equipment (quadrats) or time-intensive point counts and this feature contributes to the popularity of categorical scales for various sampling purposes in ecology (e.g. the Braun-Blanquet scale for vegetation assessments; Wikum & Shanholtzer 1978). It is also much cheaper to implement than more quantitative methods. The categories should ensure that sampling error is minimised and the LOF scale's unevenly sized categories make it particularly straightforward to assign correct rankings at the low (LOF 0 and LOF 1) and high-end (LOF 5) of the scale. It is straightforward to correctly identify biofouling scenarios in LOF 2 when macrofouling is present but very clearly at low levels of cover (1–2%). Estimating specific percentage cover of curved or complex surfaces, or assigning correct ranks for categories of even 10% bins, is more difficult and unreliable without sampling equipment. Nonetheless, diligence is still needed when using the LOF method, especially when biofouling percentage cover is near the boundaries of categories (Figure 2).

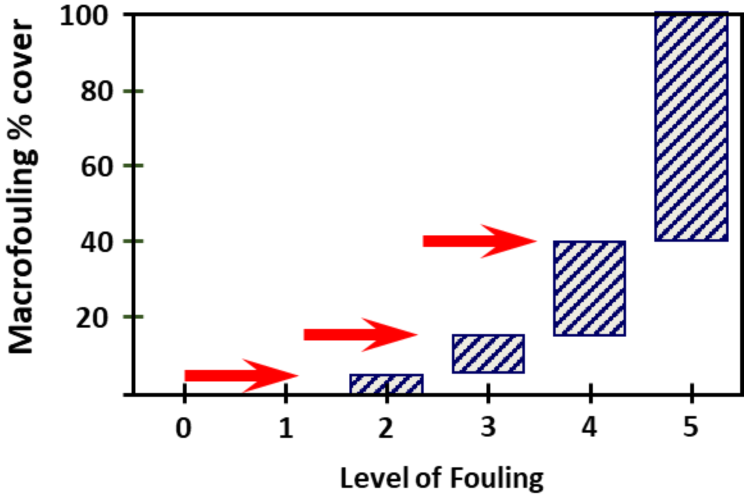


Figure 2. LOF categories are defined by ranges of biofouling percentage cover that are not evenly sized. Errors occur most often for large or complex surfaces, or in cases where biofouling percentage cover nears the range edges of different categories (red arrows).

The alignment of percentage cover and species richness in the original definitions of LOF ranks follows natural gradients of biofouling. When the LOF method was originally developed, there was a correlation between percentage cover and richness (Floerl et al. 2005). In general, as duration of submergence of a surface in the sea increases, the amount of space colonised increases (percentage cover), and the number of species within the biofouling community also increases. This is the classic relationship that underpins successional processes in ecological communities until the late-successional community is established (Magurran 2004). However, exceptions to the general trend occur whereby quite diverse communities can occupy relatively small areas and single species (or taxa) can occur at high levels of abundance or cover (Figure 3). This may be more common in vessel biofouling as several factors can influence community composition that may drive these patterns, including the effects of antifouling and hull maintenance strategies, periodic movement and the impact of hydrodynamic flow, and tolerance of biocidal surfaces. For this reason, LOF categories should be determined using categorical percentage cover alone rather than in combination with richness (Table 1; see also Davidson et al. 2021).

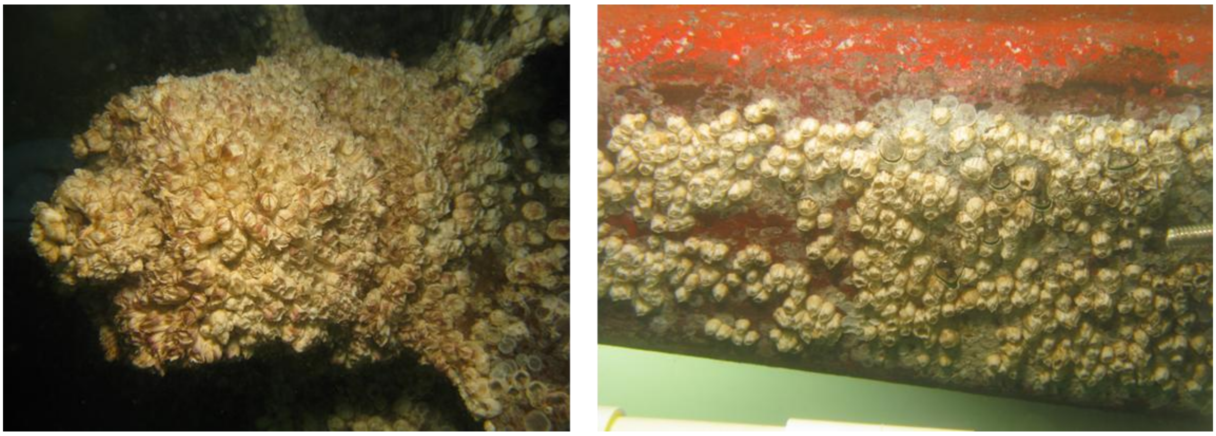


Figure 3. Examples of high percentage cover of boat niche areas (LOF 5 for a propeller and keel bottom) with an apparent taxon richness of one (barnacles).

Table 1. LOF categories of biofouling. The LOF rank, percentage cover, and taxonomic richness are described from Floerl et al. (2005). New guidance highlights that percentage cover ranges for assigning LOF ranks is the defining characteristic for determining LOFs and richness should not be used to make determinations.

LOF rank	Macrofouling percentage cover	Macrofouling taxonomic richness	Considerations / updated guidance
0	Nil	Zero	There are no new considerations for LOF 0
1	Nil	Zero	There are no new considerations for LOF 1; care is needed to distinguish biofilms from macrofouling in some instances
2	1–5%	Only one taxon	In general, species richness will be low when cover is low, but a diverse assemblage of several taxonomic groups can occur in small biofouling patches such as LOF 2
3	6–15%	One single or several different taxa	There are no new considerations for LOF 3; taxonomic richness was not determinative in the original description of this category
4	16–40%	More than one taxon	It is possible to have a high percentage cover of biofouling with just one species / taxon; percentage cover criteria take precedence when allocating ranks
5	41–100%	Diverse assemblages	It is possible to have a high percentage cover of biofouling with just one species / taxon; percentage cover criteria take precedence when allocating ranks

3.1. LOF category descriptions and images

A guide with images and schematics that describes LOF categories is available as a supplement to this report (Davidson et al. 2019). The categories are briefly described here with new additional images and notes on pitfalls to avoid when assigning LOF ranks.

LOF 0 is a straightforward determination to make in the field (Figure 4). An absence of both biofilms (slime) and macrofouling is usually rare, typically only associated with very recently deployed vessels or with recently applied antifouling. The absence of biofilms should be validated by touching the surface being viewed since light biofilms can be difficult to detect by looking alone.

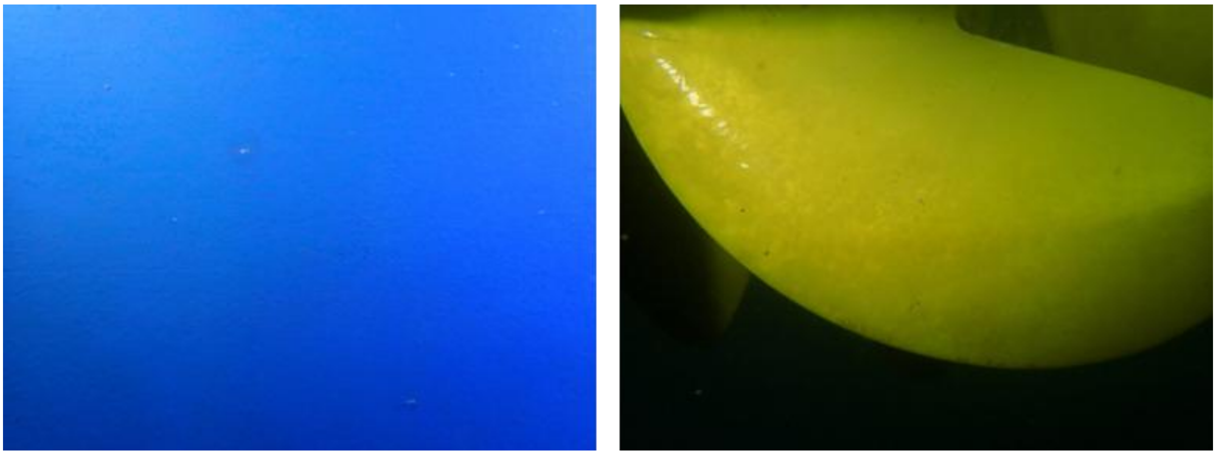


Figure 4. Examples of LOF 0 observed on the hull and propeller of recreational boats.

Although **LOF 1** is usually a straightforward LOF ranking to assign in the field, relatively new observers can be surprised by the various ways biofilms appear on submerged vessel surfaces. There must be zero macrofouling to assign this category correctly, but biofilms can develop in relatively thick layers, sometimes covered in sediment and particulate matter, and they can develop filaments that protrude from a vessel surface (Figure 5). These various forms of flat encrustations or filaments can superficially appear like bryozoans or filamentous seaweed. Moreover, there are small, delicate bryozoans that grow along stolons that can look like strands of biofilm (e.g. *Bowerbankia* species). In most cases, these possible misidentifications and erroneous LOF allocations can be distinguished and avoided with experience and familiarity with biofilms and biofouling taxa. In addition, gently wiping the surface with the hand often helps with the decision: biofilm is dislodged without effort, while even fragile bryozoans or hydroids require firmer action to dislodge.

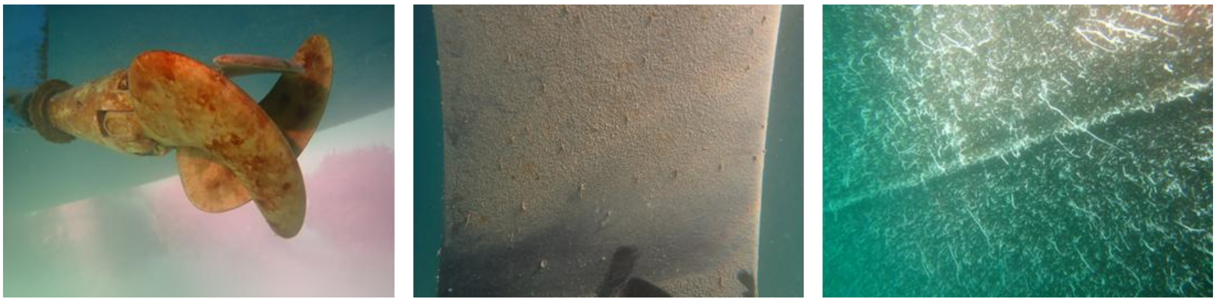


Figure 5. Examples of LOF 1 on a propeller, rudder, and hull surface with different appearances, including patchy thin encrustations (left), thick encrusting coated with sediment (centre), and filamentous (right).

The **LOF 2** rank ranges from the presence of one macrofouling organism to 5% cover of invertebrates or algae on the surface being observed (Figure 6). At the bottom end of this category LOF 2 is easily determined because the mere presence of an invertebrate or algal species is enough to separate this category from LOF 1. At the upper end of this category, it is far more difficult to distinguish between LOF 2 and LOF 3 and accuracy training for reliable estimation is needed.

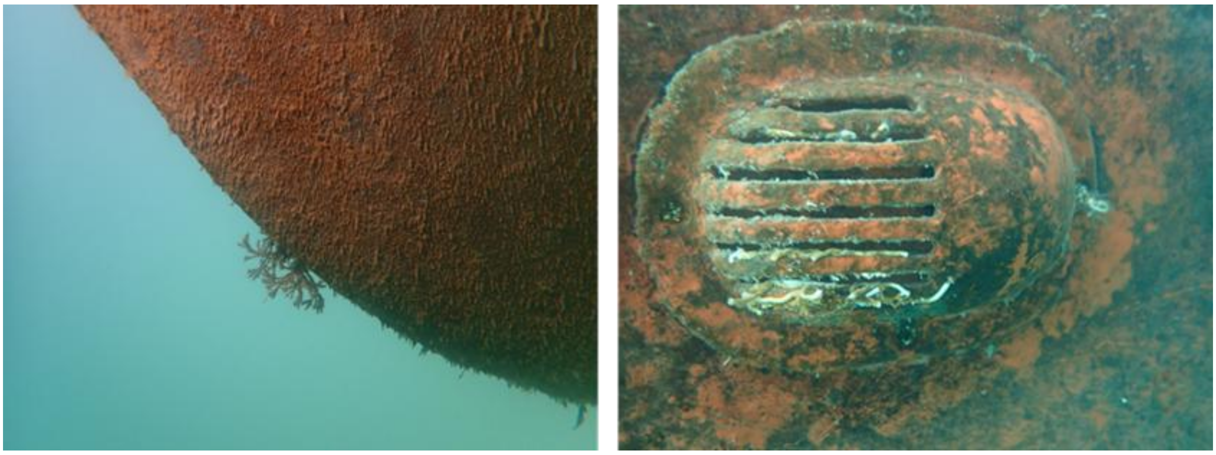


Figure 6. Images of LOF 2 observed on the bow hull of a boat and a vessel intake.

The percentage cover range for **LOF 3** is from 6% to 15% (Figure 7), which is bound at the upper and lower ends by other categories that are not easily distinguished unless strong accuracy training and validation occurs. Margin calls, such as differences of a few percentage around 5% cover and 15% cover can lead to misassignment of LOF ranks. These can be consequential in management scenarios that designate thresholds for action (e.g. cleaning or other management action) between LOF 2 and LOF 3, as occurs in some regions of Aotearoa New Zealand.

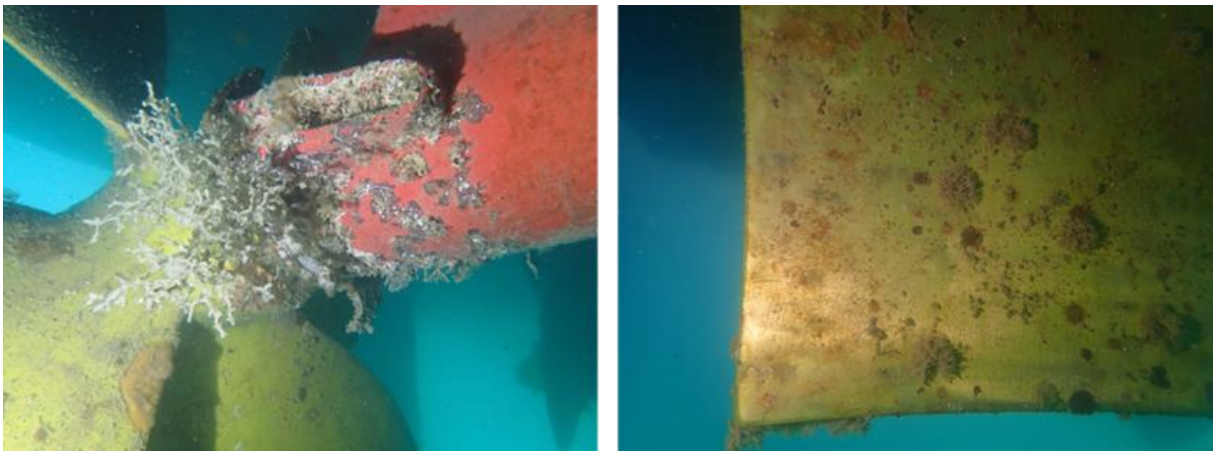


Figure 7. Validated images of LOF 3 on niche areas, including the forward-facing side of a propeller and propeller shaft (left), and the trailing edge of a rudder (right).

LOF 4 ranges from 16% to 40% (Figure 8) and has similar challenges to LOF 3 in terms of correctly assigning surfaces to this category. At the upper and lower bounds, misapplications are likely, but LOF 4 has a larger percentage cover range than LOF 3 which should mean fewer sampling errors occur when allocating this rank.

Figure 8. Examples of LOF 4 on a vessel's running gear and keel.

LOF 5 has the largest percentage cover range in the entire scale and can be confidently assigned in scenarios that have much higher than half of the surface area covered in biofouling. In this sense, it is similar to LOF 2 in terms of easy and reliable assignment of this ranking since it is at the terminal end of the whole scale. There is a lot of room for error within this ranking; as the largest percentage cover category (41% to 100% cover; Figure 9), practitioners can be quite substantially inaccurate in terms of a percentage cover estimate and still remain within the bounds of the category for correctly assigning LOF 5.

Figure 9. Examples of LOF 5 on a vessel's hull and propeller shaft / strut.

4. FIELD METHODOLOGY

Methods for generating LOF values on boats vary by how underwater surfaces are accessed for observation. These include diver, snorkeller, ROV, pole-mounted cameras (pole-cams), and on hard stand. Here, we describe diver-based surveys using LOF, which is a common approach to using the method by managers and scientists. We also recommend this method as the most balanced in terms of consistently achieving accuracy while maintaining efficiency. We then describe other approaches to emphasise aspects of sampling that differ from the diver method. In Aotearoa New Zealand, access to boats for compliance monitoring or surveillance varies by regional and central government agencies using the method. Each entity has a preferred approach, often driven by the type and scale of work being done, which ranges from twice yearly censuses of whole populations of boats (thousands of boats over a period of weeks) to sampling events at marinas (dozens of boats over a few days) and compliance monitoring of newly arrived vessels (single or several boats within a day). Despite variation in approaches, consistency and accuracy can be maintained within and among groups such that comparable standards are achieved among regions to ensure data quality and for informative interpretation of biological and boater trends. The guidance and tools from this project should promote the adoption of quality assurance protocols to ensure accuracy and precision of practitioners.

4.1. Diver method

After entry to the water, a dive team should sample a boat from stern to bow. One observer should make judgements on LOF per surface, per boat. A dive buddy can dive with the observer as safety support, to take images (if needed), or dive on a different boat in an adjacent berth depending on dive safety protocols. Surface support should tend divers, have a visible dive flag, interact with the public (on the marina or boaters on the water), and possibly record data. A dive boat is needed for areas outside of marinas such as mooring fields and anchorages. For most scenarios, Aotearoa New Zealand's regulations for occupational diving apply and need to be met.

Data recording can be done underwater by the diver using a dive slate and underwater data sheet. This approach is efficient and tables printed on underwater paper allow LOFs for each hull and niche area to be clearly documented or the surface noted as absent. Full face masks and communication units can also be used for verbal reporting of LOFs by divers to field team members at the surface. In this case, data could be entered directly into a database on a tablet. Both of these approaches to data recording – diver scribe or verbal reporting – are fit for purpose and depend on whether equipment is available to dive teams.

The observer diver should record (or verbally report) LOF ranks of all hull and niche areas present on a boat. The diver should be familiar with component niche areas of boats (what they are called and what they look like) and the data entry format prior to surveys. For the fully stratified breakdown of hull and niche areas, with subsequent use of the LOF calculator

(Section 5.2), an example of a data entry table for surveying many boats sequentially is shown in Table 2. Any missing surfaces (e.g. if rudders are absent on motorboats or thrusters are not present) should be confirmed as not applicable to avoid possible mistaken data entries.

Table 2. An example of a data sheet for recording LOFs on vessels using the fully stratified version of hull and niche areas per boat.

Submerged surface	**LOF ranks per surface**					
	Boat 1	**Boat 2**	**Boat 3**	**Boat 4**	**Boat 5**	**…Boat X**
Rudder						
Skegs / legs / struts						
Propeller & propeller shaft						
Stern hull						
Intakes / outlets						
Mid-hull						
Keel						
Dock block areas						
Other*						
Thrusters						
Bow hull						

* 'Other' includes smaller niche areas such as transducers, knot meters, stabilisers, anodes, or other protrusions or surfaces not otherwise listed. A single amalgamated LOF should be assigned to these minor niche areas.

In the fully stratified approach for LOF recording of hull and niche areas, the hull should be subdivided into three sections, corresponding to one-third sections of hull along the boat's length. This is intuitively easy to implement and divides the hull into stern, mid-boat, and bow sections. This approach allows the largest surface (the hull) to be compartmentalised for LOF ranks, and the LOF calculator can operate at this level of hull subdivision (Section 5.2). This approach may promote accuracy by breaking down a large area into three parts and allowing divers to record LOFs without moving back-and-forth between large hull areas and niche areas.

When the data sheet is ordered appropriately, the diver should encounter each hull / niche area (roughly) in sequence, with no need to dive around the same areas twice. Each hull or niche can be viewed as an independent LOF allocation by the diver, and the majority of LOF assignments occur in a single view rather than a grouping of many surfaces that are then combined mentally (by the diver) for a single score. In this way, the fully stratified diver approach should promote accuracy above other approaches that require whole-vessel allocations, especially in cases when biofouling percentage cover is at the margins of two LOF categories (Figure 2).

After practitioner feedback from a workshop, held in Auckland in June 2022 (Appendix 1), it was decided that the method and LOF electronic application (with LOF calculator) should offer three different ways to enter data that would cater to the range of preferences of attendees and most practitioners within and outside of Aotearoa New Zealand. These are:

- A fully stratified approach (this section, described above, and recommended for highest accuracy)
- A hybrid stratified approach that has three components – hull, keel, and running gears
- An in-field allocation of a whole-boat LOF

The diver method for the hybrid stratified approach differs from the fully stratified approach by assigning LOF ranks to just three strata: the entire hull area, the keel, and all niche areas. These three rankings can be converted to a whole-boat LOF score using the LOF calculator. This approach has fewer data entry requirements but is more likely to introduce observer error. It is useful in cases where marginal LOF rankings are occurring (e.g. distinguishing between LOF 2 and LOF 3) without relying on a whole-boat LOF assignment but without entering LOF data for each hull and niche area separately.

The in-field allocation of whole-boat LOF has the potential for introducing the most sampling error in LOF assignment of the three diver methods, but is the most efficient and preferred approach when easy / confident scenarios are encountered. These include straightforward allocations of LOF 1 (no macrofouling), LOF 2 (macrofouling presence and certainly less than 5%) and LOF 5 (confident appraisals that more than half of the boat's underwater surface area is covered in biofouling). However, allocations of LOF 2 (at the higher end of its range), LOF 3, and LOF 4 are prone to sampling error (misallocations of ranks).

4.2. Non-diver methods

The **snorkeller** approach to applying the LOF method is very efficient and preferred by practitioners that need to survey many boats in short periods of time. Pairs of field workers, one in the water and one at the surface, can move swiftly to survey individual boats and move among boats[1]. It is the least gear intensive in-water approach. The method requires good snorkelling and free-diving skills such that submerged surfaces can be observed for long enough to make accurate determinations of LOF ranks. Practitioners in Aotearoa New Zealand tend to combine this approach with whole-boat LOF allocations because the snorkeller free dives to make a determination and returns to the surface to convey the LOF rank to the data recording person using their hand (the number of fingers held up indicates a score from zero to five).

[1] Diving and snorkelling guidelines and associated Health & Safety protocols for field work vary between organisations. The descriptions here are intended as practical recommendations but it is the responsibility of the organisation conducting the surveys to ensure compliance with all relevant H & S and occupational diving protocols.

The **remotely operated vehicle (ROV)** approach for LOF applications is used in some regions of Aotearoa New Zealand and has been used for scientific and operational research on ship and boat biofouling (Davidson et al. 2009; Leonard 2009; Floerl & Coutts 2011; Zabin et al. 2018). Applying LOF ranks on boats relies heavily on ROV operator ability but there are fewer safety considerations using ROVs because nobody enters the water. Image quality from ROVs can be higher than for diver-operated cameras, although conditions and turbidity have an effect on the efficiency of surveys. The main limitation for LOF applications using ROVs (relative to divers) is an absence of peripheral vision and touch, and manoeuvring into positions to observe biofouling organisms that are not easily accessed on constrained or complex surfaces of a boat (Zabin et al. 2018). Misidentifications are more likely when observers are not in the water themselves. Nonetheless, an ability to assess LOF using a fully stratified method is well suited to ROV use. The fully stratified approach may be more appropriate for ROVs, in particular, compared to the hybrid method or whole-boat allocation in the field.

Hull-cams or pole-cams are a means of accessing underwater boat surfaces for LOF surveys without the ability of the camera to fly into position. Hull-cams usually have wheels and magnets or thrusters to remain on a hull (Floerl & Coutts 2011) and were used during the original development of the LOF method (Floerl et al. 2005). Pole-cams are usually fixed to the end of a telescopically-extendable pole to provide enough reach to access deeper areas of boats (Davidson et al. 2010). In both cases, real-time imagery can be observed at the surface by operators and LOF determinations can be made. The positive and negative factors for these tools are similar to ROVs, with safety issues at a minimum but misidentification of organisms, biofilms, and hull surfaces possible. Hindered access to certain niche areas is an important drawback – hull-cams cannot easily manoeuvre outside of hull areas while pole-cams can be restricted in terms of articulating the pole to view sections of a boat and an entire side of a boat may be inaccessible to pole-cams depending on berthing / dock configurations.

The fully stratified, hybrid, and whole-boat LOF methods can all be carried out on **hard stand**, sling or slipway soon after a vessel is removed from the water. There is no impediment to making LOF determinations on land, but limited access to vessels make this a relatively unused approach for applying LOF methods. If boat yard staff were trained, this may be an opportunity for citizen / industry science to contribute to LOF monitoring.

4.3. Tips for confident and reliable LOF allocation

There are several drivers of LOF misapplication and inter-observer differences, each of which can compromise accuracy and precision when acquiring LOF data. The large size of surfaces or the complexity of surfaces are important considerations when assigning LOF ranks to hulls and niches. For example, deriving whole-boat or whole-hull LOF scores while moving around a vessel to build a mental picture of a surface that cannot be observed in one view is challenging. Likewise, observers may not intuitively know how much surface area they are examining relative to biofouling observed on complex propellers with front and back faces of multiple propeller blades connected to a cylindrical shaft. Despite this, some practitioners have suggested that smaller scale sub-component LOF allocations can be more difficult to determine than the larger scale allocations for whole boats.

Another driver of misallocation that is very common is the marginal calls that must be made when biofouling percentage cover approximates the borderline value of two LOF ranks (Figure 2). There is little that can be done to resolve this issue outside of regular accuracy checks using validation methods, some of which may be addressed by using the electronic application training tools from this project. One version of this issue that is more readily resolved occurs when a single or small occurrence of biofouling is missed when it is present, resulting in a reported LOF 1 when the correct ranking was LOF 2. Ensuring coverage of all relevant surfaces is key to avoiding this misapplication. This is more challenging when practitioners are using ROVs or hull / pole cameras and may not be able to orient the camera toward every surface.

Developing strategies to understand and 'anchor' visualisations of percentage cover is a useful tool to combat misapplications, especially for marginal calls between LOF categories. The benefit of the LOF method is that there is no sampling equipment needed, but practitioners should understand relative sizes of surfaces and patches of biofouling. One example of this is to use the elbow to fingertip length, which approximates 0.5 m, as an 'imaginary' side of a quadrat (Figure 10). Using this as an anchoring image, especially for larger surfaces (e.g. hulls) a handprint within that space is approximately 5% cover (Figure 10). It is also useful to get familiar with variation in cover distributions, such as clumped versus dispersed, to ensure better LOF allocations.

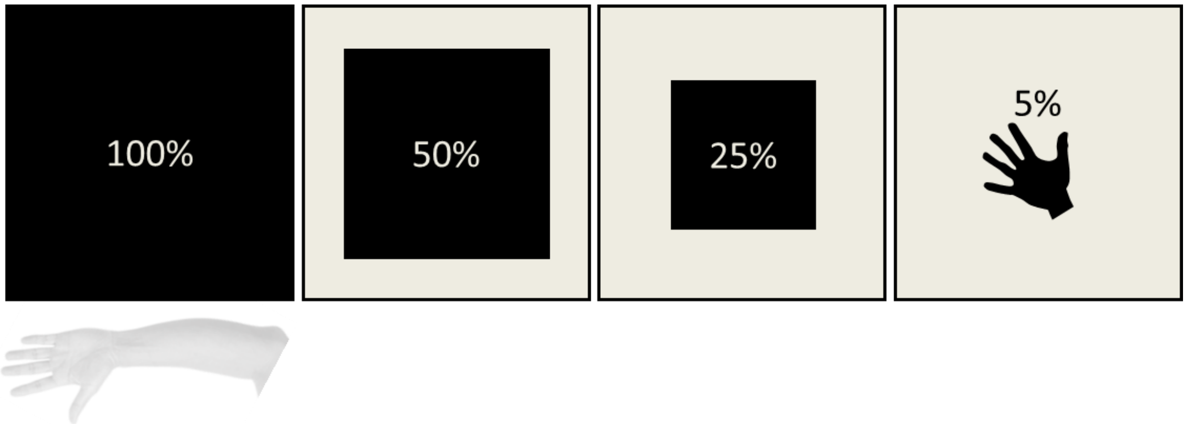


Figure 10. Examples of percentage cover and tips to 'anchor' an observer to a correct estimation. The distance from a person's elbow to the tips of their fingers approximates 0.5 m (left). This is useful in the context of LOF allocations where no quadrats or measurement equipment are used. Understanding what one-half and one-quarter of this area with a central clumped distribution looks like is helpful. The size of a person's hand within an 'arm-sized' quadrat is approximately 5% cover (right).

Misinterpreting biofouling taxa or surfaces, such as hull and coating blemishes or the occurrence of biofilms that look like macrofouling, is also a source of error when allocating LOF ranks. This occurs more often for observers that are not underwater, using camera equipment rather than direct observations. Examples include barnacle scars that can have the appearance of encrusting species, pitted surfaces that appear like the texture of biofouling encrustations, and flaking hull coatings that have an appearance of organisms that move in the current. Divers and snorkellers can quickly touch these areas to make accurate determinations. Experience and operator expertise with camera equipment can help overcome these issues for observers using ROVs and hull / pole cams.

Lastly, aggregating multiple LOF values for several surfaces in your head will inevitably lead to inaccurate LOF allocations unless periodic ground-truthing and training occurs. For this reason, we recommend the fully stratified approach to LOF allocations which simplifies LOF decision making in the field and automates (standardises) aggregation for whole-boat rankings.

4.4. The need for accuracy and precision during LOF allocation

Accuracy and precision are important criteria for the use of ecological sampling and assessment methods (Andrew & Mapstone 1987). The Oxford Dictionary defines 'accuracy' as *the degree to which the result of a measurement, calculation, or specification conforms to the correct value or a standard*. It is thus a measure of veracity and, in this project's context, describes the ability of a biosecurity practitioner to allocate the correct LOF to a vessel or part of a vessel.

Precision, in turn, is defined as *the degree to which an instrument or process will repeat the same value*, and thus a measure of reproducibility. In the context of vessel biofouling surveillance, it describes the degree to which an individual practitioner would allocate the same LOF to vessels with similar biofouling profiles, or the concordance of LOF scores allocated to the same scenario by multiple practitioners or regional teams of practitioners. Figure 11 illustrates the concepts of accuracy and precision in the context of vessel biofouling inspections. Scenario (d) is the competency level that teams of practitioners should aspire to perform at.

Variations in accuracy and precision of LOF rank allocations to vessels targeted for surveillance can arise from multiple sources, such as:

- Differences between practitioners in familiarity with or interpretation of the LOF rank definitions;
- Variation in how individual observers make decisions on LOF rank allocation during successive vessel inspections;

- Differences in how whole-vessel LOFs are derived (e.g. via allocation of an overall LOF at the end of an inspection vs. post-inspection aggregation of multiple niche-level LOF ranks);
- Individual intuitive approaches of 'rounding up or down' LOF ranks depending on particular features or conditions encountered during an inspection.

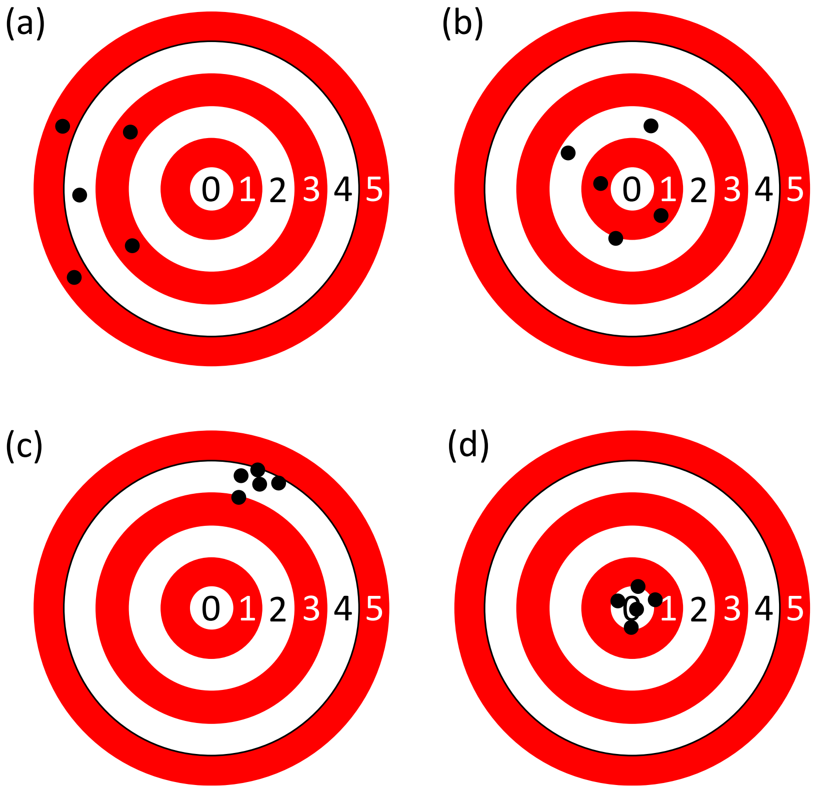


Figure 11. Accuracy and precision in the context of the LOF scale. The horizontal numbers 0–5 in each target refer to the six LOF ranks. The black dots represent LOF ranks allocated by individual practitioners. The assumption in all target scenarios is that the correct rank is LOF 0 (the centre). (a) Low accuracy (all estimates are far from the correct value) and low precision (wide variation between individual estimates). (b) Higher accuracy (estimates are closer to the correct value) but still low precision (wide variation, with different LOF ranks allocated by different practitioners). (c) Low accuracy (estimates far from the correct value) and high precision (low variation between practitioners). (d) High accuracy and high precision. The outcome described in (d) should be what individuals and teams of practitioners should strive for.

Robust and defensible surveillance or compliance monitoring programmes require high levels of accuracy and precision in LOF rank allocation within and between regional teams of practitioners. In the first instance, high familiarity with the approaches described above (Section 4 – 'Field methodology') is important. In addition, specific training exercises for individuals and teams of practitioners can be used to reach and maintain desired levels of accuracy and precision. Suggested training activities are described in Appendix 1.

5. VESSEL MORPHOMETRICS AND LOF CALCULATOR

A key challenge for retaining accuracy when using LOF categories is assigning a single rank to a large area. This occurs routinely for assigning 'whole-boat' LOF ranks encompassing all hull and niche surface areas from stern to bow of a boat. Regardless of water clarity, this cannot be done by an observer viewing all surfaces (port and starboard) at the same time. Practitioners must therefore assess multiple surfaces and then assign an LOF rank for the composite surfaces they have observed, often an aggregation of rapidly assessing multiple surfaces one after the other. We examined vessel morphometrics – the sizes of different underwater components of vessels and their relative contribution to the entire underwater surface area of boats – to inform applications of whole-boat LOF. We then developed an LOF calculator that can efficiently and automatically provide whole-boat LOF rankings from multiple hull and niche LOFs. The calculator uses the morphometric analysis of hull wetted surface area (WSA), and the contribution of niche areas to total wetted surface area (TWSA), to apply appropriate weightings to LOF scores from multiple locations of the same vessel in order to derive a whole-vessel LOF score.

Estimating the surface areas of hulls and submerged components of boats and ships plays an important role in naval architecture to understand propulsion dynamics, power and size of running gears, amount of anticorrosion and antifouling coatings needed to paint a vessel, and environmental discharges from vessel surfaces (Bertram 2012; Bakker & van Vlaardingen 2017). These calculations have also been used to estimate surface areas available to biofouling organisms as a predictor of risk for introductions of marine NIS. For example, Moser et al. (2016) estimated the global fleet of commercial ships has approximately 325×10^6 m^2 of vessel surface area in transit around the world. Estimates of WSA can be used to differentiate invasion risk for different ports or bioregions, or for different ship types (Davidson et al. 2018; Miller et al. 2018). The morphometrics of ships has also been calculated to understand the relative contribution of different niche areas to and differences among ship types (Moser et al. 2017). We adopted a similar approach for boats in this study to provide a better understanding of the relative contributions of hull and niche areas to TWSA of boats. These data underpin calculations for aggregating multiple LOFs of a boat to a single whole-boat LOF or provide practitioners with better estimates of relative size of submerged surfaces for more accurate application of LOF methods.

5.1. Vessel morphometrics

Measurements of vessel and niche area dimensions were taken from boats on hard stands at a boat yard in the Auckland area (n=14 boats). These boats represented a broad range of manufacturers and models and we did not measure multiple versions of the same model of boat. We do not have data on the population sizes of different boat types and therefore used the boats we sampled to inform a general model of hull and niche area contributions to TWSA for yachts and motorboats. Two observers measured and recorded the dimensions of each vessel, including vessel length, waterline length, beam, and draft. They also measured the dimensions of all niche areas encountered, with detailed notes and diagrams of configurations of each (Figure 12).

Figure 12. Examples of niche areas measured from boats on hard stand. Clockwise from top left: propeller, shaft, and skeg; rudder; anode; transducer; thruster tunnel and propeller. For each niche area, basic measurements of length, breadth and height were taken, plus surface dimensions of cylinder and circular areas used for calculating surface areas.

5.1.1. Hull surface areas

There are several equations available for calculating hull WSA, each with different data requirements (Bakker & van Vlaardingen 2017). We used a version of the Denny–Mumford equation for calculating WSA of hulls. The Denny–Mumford equation is a commonly used approach for WSA calculation that is relatively straightforward to calculate (Moser et al. 2016). The approach requires basic measurements of vessel dimensions (length, beam, and draft) and a blocking coefficient which considers the shape of the hull. Blocking coefficients are an estimate of how hull configurations (shapes) differ from a rectangular block and contribute to WSA calculations that consider the curvature and shape of a hull. The version of the Denny–Mumford equation used in this study does not require displacement volume or several other variables that cannot be easily obtained for boats. For this study, a standardised blocking coefficient was applied to yachts and motorboats derived from Bakker

& van Vlaardingen (2017). Two separate calculations are applied to yachts and motorboats because they differ in key aspects of hull configuration and niche area sizes.

The Denny–Mumford equation is as follows: WSA = L * (1.7 * T + B * Cb), where

- WSA is wetted surface area
- Cb is the blocking coefficient
- L is waterline length
- T is the draft, excluding the keel
- B is the beam (or breadth / width)

The blocking coefficients for sailing yachts and motorboats were 0.41 and 0.45, respectively (Bakker & van Vlaardingen 2017)

5.1.2. Niche surface areas

Niche area measurements were used to calculate surface areas visible to observers, taking care to include all sides of appendages and niche areas where appropriate (Table 3). Surface area measurements were then averaged for each type of niche for sailing yachts and motorboats to determine relative contributions to overall area for underwater surfaces for both vessel types. For several niche areas, the calculations of overall surface area was relatively straightforward if the structures had flat surfaces and uncomplicated configurations (e.g. rudders, keels) or simple circular or cylindrical shapes (e.g. propeller shafts, thrusters, outlets). Other niche areas had complex configurations and required several measurements of different subcomponents. For example, propellers varied in complexity, with some requiring straightforward calculations of the 'swept area' of a propeller and the shape of the blades, whereas others required amalgamated measurement of irregularly shaped components. If there were multiple versions of the same niche on a vessel (e.g. two propellers, several through-hull outlets), these were combined to a single surface area for that niche for each boat.

Table 3. Niche area surfaces and measurement details for determining surface areas of various parts of submerged surfaces of boats. 'Number' refers to the amount of a particular type of niche area on a vessel (there can be multiple versions of the same niche on a boat).

Niche area	Details
Rudder	Height, width, thickness
Skeg / leg / strut	Height, width, thickness, and configuration
Propeller	Diameter of full propeller, number of blades
Propeller shaft	Diameter, length
Keel	Top length, bottom length, height, thickness
Through-hull fittings	Outer diameter, inner diameter, number of fittings
Anodes	Height, width, thickness
Transducer	Long axis, short axis, shape / configuration, number
Impellor	Diameter
Covered intakes / outlets	Length, width, height, number
Dock block areas	Length, width, number
Stabilisers	Length, width, number
Bow thruster	Tunnel diameter, tunnel length, propeller diameter, number of blades

5.2. LOF calculator

For each vessel, the sum of hull WSA and all niche surface areas provided a TWSA. These values (per boat) were used to generate a weighting for each surface in the overall calculation of whole-boat LOF. The weightings are the relative contribution (percentage or proportion) for each sub-area to a boat's TWSA. The average weightings within each vessel type provided the final weighting value for yachts and motorboats (i.e. two distinct sets of weightings for two types of vessel). The hull was divided into three sections corresponding to one-third of the length of a vessel (see Section 4) to provide the option of compartmentalising hull LOF ranks rather than a single score for the largest surface of a boat. This makes practical sense for breaking down larger surface areas and is also linked to biofouling accumulation on vessels which can vary from bow to stern of vessel hulls because of hydrodynamics and coating efficacy. For practitioners, a subdivided hull approach provides a straightforward method to assess hull LOF for three sections – stern hull, mid-vessel hull, and bow hull – which can then be used to calculate whole-boat LOF. The weighting of each of these three hull sections is not equal because these hull sections are shaped differently. The bow hull area is smaller than mid-hull areas because vessels are narrower and longitudinally curved at the bow. The stern hull of motorboats is equal to mid-hull area as they are shaped similarly, but stern hulls are smaller than mid-hull areas on yachts. The final weightings for hull and niche areas of yachts and motorboats are shown in (Table 4).

Table 4. Weightings for yachts and motorboats, including three hull areas (stern, mid, and bow hull) plus several niche areas. These proportions represent the amount of surface area each component contributes to boat total wetted surface area (TWSA). For example, rudders contribute 3.7% of the underwater surface area (on average) of yachts.

Sailboats or yachts			Motorboats	
Stern hull	0.2697		Stern hull	0.3454
Mid-hull	0.3596		Mid-hull	0.3454
Bow hull	0.1798		Bow hull	0.1727
Rudder	0.0371		Rudder	0.0113
Prop & shaft	0.0143		Prop & shaft	0.0587
Skegs / struts	0.0049		Skegs / struts	0.0333
Keel	0.1230		Dock blocks	0.0173
Dock blocks	0.0033		Inlets / outlets	0.0026
Inlets / outlets	0.0007		Thrusters	0.0118
Thrusters	0.0066		Other	0.0015
Other	0.0008			

Calculating whole-boat LOF from multiple component LOF values uses weightings from vessel morphometric measurements (Table 4) and the midpoint value for each LOF category (Table 5). Although midpoint values for broad categories can distort the actual variation observed when assigning LOF ranks to vessel surfaces, a quantitative value representing the category, rather than the categorical number, is required to provide a standardised approach for whole-boat LOF calculations. A midpoint of each LOF rank is a reasonable value to use, and midpoint values have been similarly used for applications of other categorical systems of environmental measurement. For example, the much-used Braun-Blanquet system of vegetation classification has similarly been tailored for converting its cover-abundance scale to the midpoint of the cover range of each category (Wikum & Shanholtzer 1978).

Table 5. Quantitative midpoint values of percentage cover for each LOF rank on the LOF scale.

LOF rank	Midpoint of the percentage cover range	Range
0	0	0
1	0	0
2	2.5	Presence to 5%
3	10.5	6% to 15%
4	28	16% to 40%
5	70.5	41% to 100%

Following the LOF methodologies described in Section 4 and the weighting approach to vessel morphometrics (this section), the LOF calculator uses a standard weighted average approach to calculate whole-boat LOF from multiple component LOFs. This involves converting the LOF category for each hull and niche area into its quantitative midpoint value

(Table 5). These LOF values are multiplied by the weighting factor for each hull and niche area (Table 4). The sum of these weighted values is then divided by the sum of the weightings, which accounts for boats that do not have all of the niche area components. For example, dock block areas of thrusters may not be present, and the calculation should account for these absences by not underweighting other components that are present. The outcome of these calculation steps provides a quantitative LOF score, which should then be converted back to the appropriate LOF ranking. The LOF electronic application (Section 6) does this calculation automatically if the basic LOF ranking data for each hull and niche area is provided by users.

5.2.1. An example of whole-boat LOF calculation

As an example to illustrate how the LOF calculator works, consider a yacht with just biofilms (LOF 1) and no macroinvertebrate or algae biofouling on three hull areas and the keel. The same vessel has heavy biofouling (>40%, LOF 5) on six niche areas (Table 6). This scenario can be encountered for vessels that have recently applied and effective antifouling coatings on hull and keel surfaces but does not have an operational profile or antifouling strategy to maintain clean niche areas.

Table 6. An example scenario of LOF ranks for hull and niche areas of a boat.

Underwater area	LOF
Stern hull	1
Mid-hull	1
Bow hull	1
Rudder	5
Prop & shaft	5
Skegs / struts	5
Keel	1
Dock blocks	5
Inlets / outlets	5
Other	5

In this scenario, the calculator converts the LOF ranks to quantitative midpoint values. These correspond to zero for LOF 1 and 70.5% for LOF 5 (Table 5). Each of these 10 values is then multiplied by their corresponding weighting for each hull and niche area. These 10 weighted values are then summed and that value is divided by the sum of the 10 weightings (Table 7). The overall outcome is that whole-boat percentage cover is calculated as 4.35%, which corresponds to a ranking of LOF 2 (presence of biofouling up to 5% cover). The calculator, therefore, provides practitioners, managers, policy makers and boat owners with a better understanding of the relative contributions of various parts of a boat's submerged surfaces and LOF ranks to whole-boat LOFs.

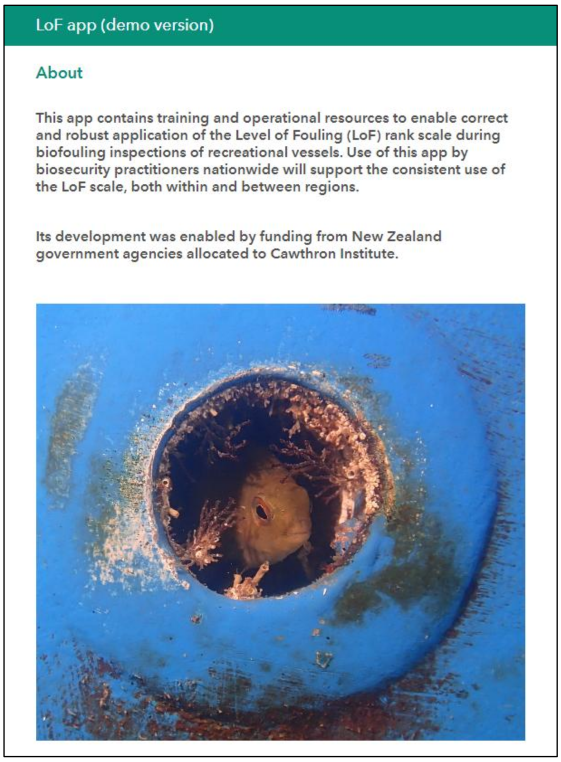
Table 7. An example scenario for whole-boat LOF calculation using multiple component LOFs. In this scenario, three hull areas and the keel have LOF 1 and all niche areas have LOF 5. The weighted average approach results in a standardised method for determining that this yacht has LOF 2 overall.

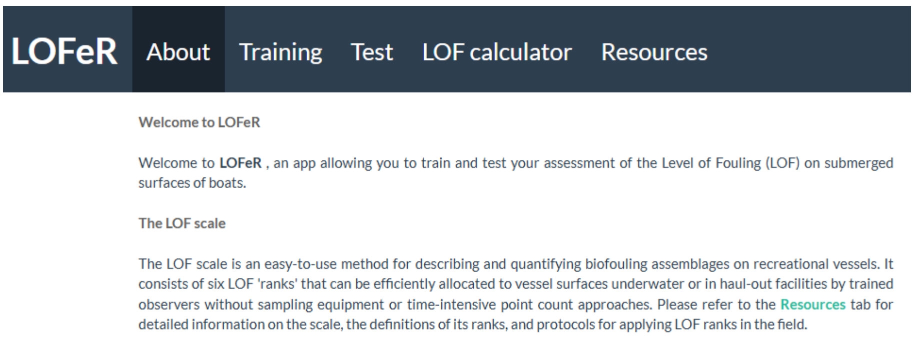
Underwater area	Weighting	Midpoint value	Product
Stern hull	0.2697	0	0.00
Mid-hull	0.3596	0	0.00
Bow hull	0.1798	0	0.00
Rudder	0.0371	70.5	2.62
Prop & shaft	0.0143	70.5	1.01
Skegs / struts	0.0050	70.5	0.35
Keel	0.1230	0	0.00
Dock blocks	0.0033	70.5	0.23
Inlets / outlets	0.0007	70.5	0.05
Thrusters	0.0066	n/a	n/a
Other	0.0008	70.5	0.05
	B		A
Sum of columns	0.99		4.32
Whole-boat percentage cover (A/B)			4.35
Whole-boat LOF			**2**

6. LEVEL OF FOULING APP

A prototype version of the LOF app (based on the ESRI Survey123 platform) was developed for demonstration to nationwide practitioners at the project workshop (June 2022) and to obtain feedback on functionality for the final version. The full LOF app was developed using the shiny app package in R. This section provides a 'tour' of the app and describes preferences expressed by workshop attendees. The final version of the app is publicly available (https://cawthron.shinyapps.io/LOFeR/) and is called the LOFeR app, based on prior work in plant ecology a derived from the BotanizeR app (Weigelt et al. 2021). This provides a user-friendly software tool for training and self-evaluation in implementing the LOF method.

The **start page** of the app provides a brief overview of the tool's purpose, as well as a menu button to enable navigation to different resources included in the app.

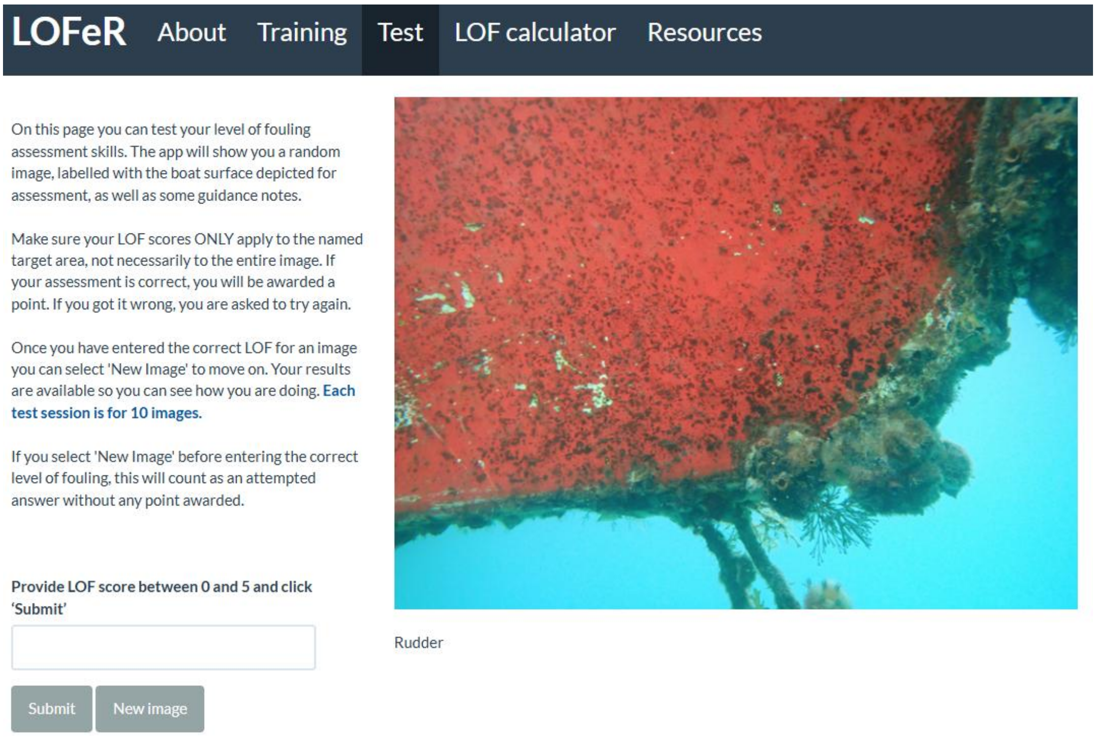




A **Methods section** contains links to:

(i) step-by-step protocols for LOF rank allocation by divers or snorkellers, and any procedural variations applying to the use of ROVs or hard-stand assessments;
(ii) methods, assumptions and equations underlying the calculation of whole-vessel LOF ranks from multiple hull- or niche-level LOF ranks, and methods for using the LOF calculator tool included in the app;
(iii) Training activities to develop, monitor, and maintain LOF skills, including was to build or maintain accuracy and precision for new and existing practitioners, and teams of practitioners.

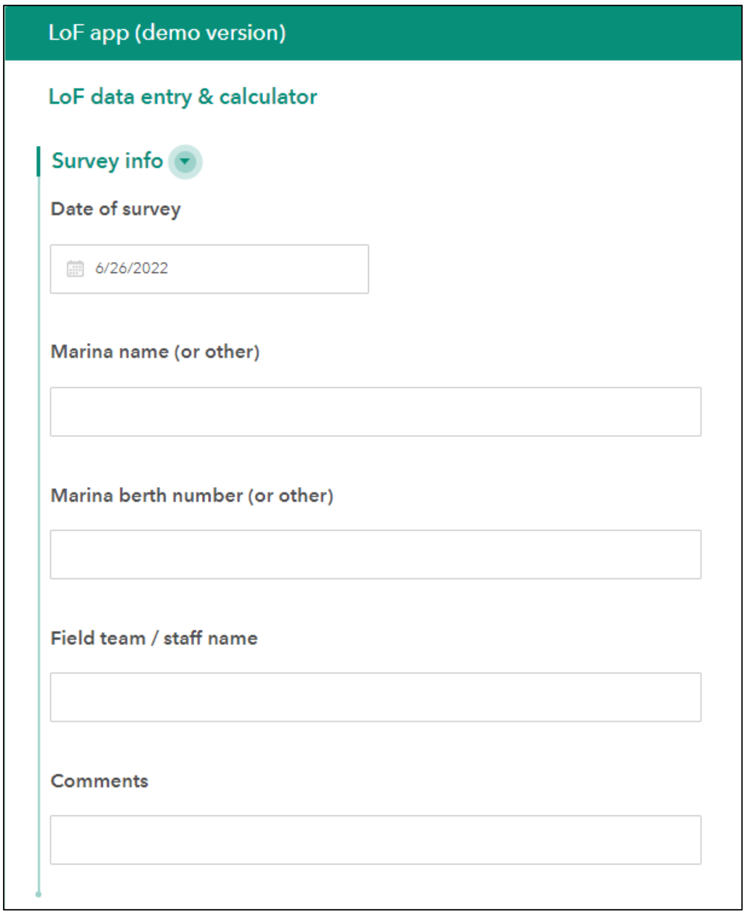
A **self-evaluation section** will allow users to determine their accuracy in the allocation of LOF ranks. Each time this feature is used, the app draws a random sub-set of 10 images from a gallery of approx. 600 images that each contain underwater views of hull or niche areas with different biofouling intensities. All images have validated LOF ranks that were determined via quantitative image analysis. Users are asked to score an LOF rank for each image as a self-evaluation tool, and are provided results on their scores, with explanations for whether or not their score is correct.

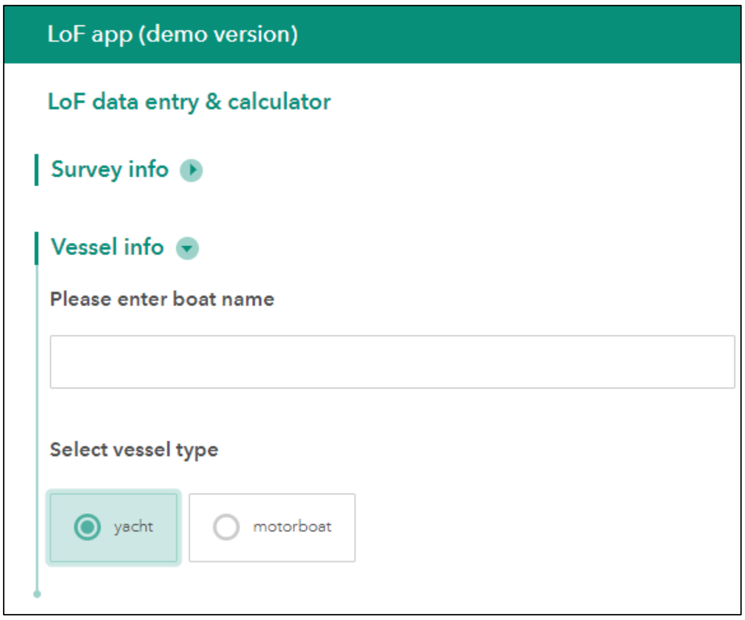


After all 10 images have been scored, the user will be provided with the proportion of images classified correctly. When used regularly over time, this feature should result in increased accuracy.

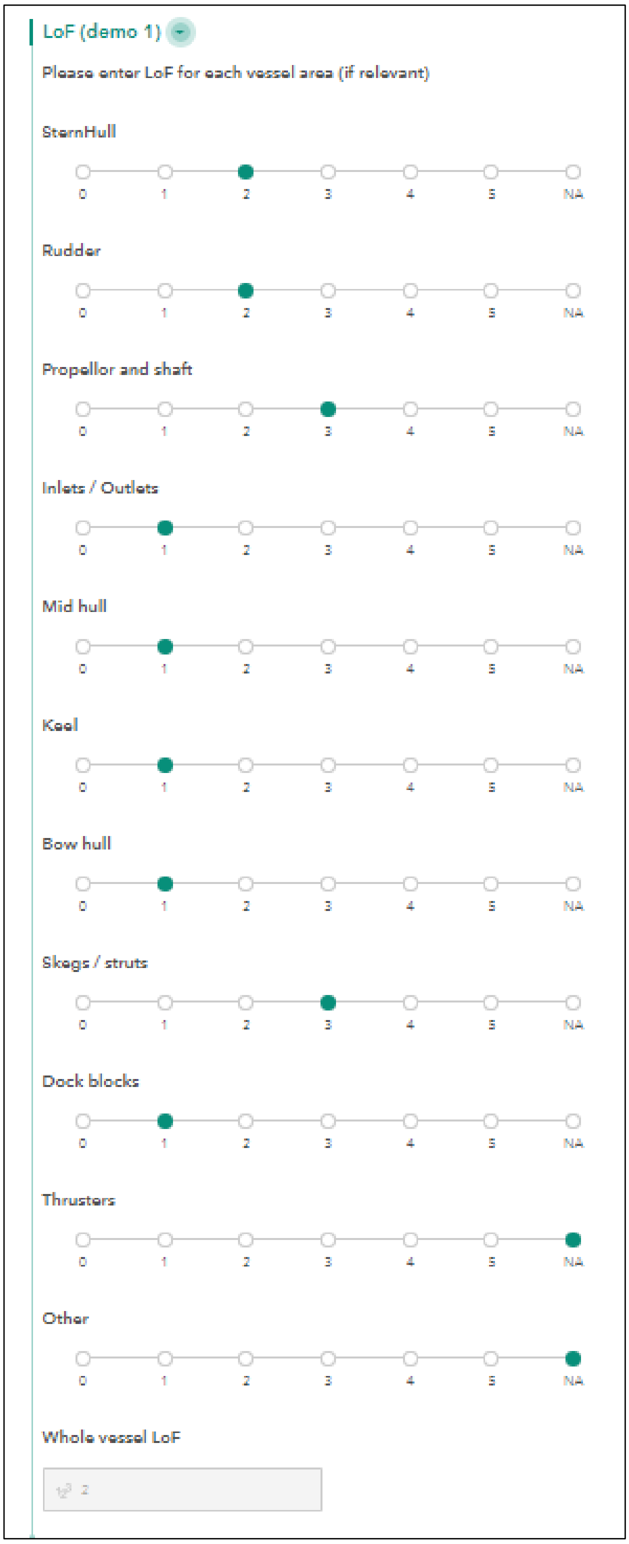
A **vessel inspection data entry and LOF calculator** section, housed in an ESRI Survey 123 partnering App, enables users to:

(i) Capture information relevant to the inspection of an individual vessel;





(ii) Enter hull- and niche-level LOF ranks collected during the inspection and calculate the whole-vessel LOF rank using algorithms drawing on the proportional representation of different vessel areas and features, as explained in the morphometric section above.



Different algorithms are used for sailing yachts and motor launches, and where hull or niche features are absent (and ‘NA’ is selected by the user) they are automatically excluded from whole-vessel LOF calculations. All input data (inspection and vessel information, any LOF ranks allocated and calculated) are stored internally.

Data for inspections undertaken using the device can be stored locally and final decisions will be made about exporting data to centralised database. Viewing, confirming, and manipulating entered data will be at the forefront of final app development for this component.

Finally, a **disclaimer** will clarify the responsibilities and liabilities of users and providers of the app. There is a standardised version of disclaimer text for legal reasons. The quality and accuracy of all resources included in the app has been validated, including the correct calculation of whole-vessel LOFs based on assumptions of that method, vessel types, and hull- / niche-level LOFs provided by the user. However, where inaccurate hull- and niche-level LOF ranks are entered by the user, the whole-vessel LOF calculated by the app may (is likely to) reflect that inaccuracy of in-field assessment.

7. SYNOPSIS

This report describes the outputs from a two-part, multi-agency-funded project aimed at developing guidance and operational resources for recreational vessel biofouling inspections using the level of fouling (LOF) rank scale. Part 1 involved the collection of extensive underwater still and video imagery on the biofouling status of >100 yachts and motorboats (around Nelson and Auckland). It also included the development and incorporation of minor modifications to the rank definitions of the LOF scale. Part 2 involved the development of operational protocols, an LOF calculator, an LOF app, and the delivery of a 1-day training workshop for nationwide LOF practitioners.

These outputs are timely given the increasingly wide use of the LOF scale as a cost-effective tool for determining the biofouling status of recreational vessels in Aotearoa New Zealand waters. In particular when LOF ranks are used to determine the compliance of a vessel with a regional biofouling threshold, it is essential that inspectors are highly accurate in their use of the scale, and that there is adequate precision at the individual and regional team levels. Since recreational vessels frequently travel between regions, consistency between regional teams of inspectors also becomes important. When this is the case, the implementation of a biofouling threshold system is applied evenly and robustly, and is based on defensible methods and approaches. Earlier in this report, we have highlighted the analogy between the LOF and the modified McLean scale for rabbit infestation. The McLean scale is a good example because it directly translates into landowner obligations around pest control under regional pest management strategies. This is similar to restrictions on vessel moving within or between regions of Aotearoa New Zealand based on their LOF ranks, involving consequences for their owners. As with any other threshold-based system (e.g. the International Convention for the Control and Management of Ships' Ballast Water and Sediments), measurements of critical response variables must be accurate, precise, and validated for these processes to be robust and defensible.

The recent emergence of formal inter-regional collaborations such as the Top of the North and the Top of the South Marine Biosecurity Partnerships presents ideal platforms for the roll-out of LOF training and skills maintenance activities, for both new and experienced personnel. We consider that annual LOF training events could be useful initiatives where teams are provided with the opportunity to measure accuracy and precision, and identify the need (if any) for training in particular aspects. They could be held indoors or at a marina for real-world scenarios. The events can be organised based on scientific principles, and their implementation and outcomes can even serve as guidance for international uptake.

8. REFERENCES

Andrew, N. L., & Mapstone, B. D. (1987). Sampling and the description of spatial pattern in marine ecology. *Oceanography and Marine Biology*, *25*, 39–90.

Ashton, G. V., Zabin, C. J., Davidson, I. C., & Ruiz, G. M. (2022). Recreational boats routinely transfer organisms and promote marine bioinvasions. *Biological Invasions*, *24*(4), 1083–1096.

Ashton, G., Davidson, I., & Ruiz, G. (2014). Transient small boats as a long-distance coastal vector for dispersal of biofouling organisms. *Estuaries and Coasts*, *37*(6), 1572–1581.

Bakker, J., & van Vlaardingen, P. L. A. (2017). *Wetted surface area of recreational boats*. Report to the National Institute for Public Health and the Environment. The Netherlands.

Bertram, V. (2012). *Practical ship hydrodynamics*. Elsevier.

Brine, O., Hunt, L., & Costello, M. J. (2013). Marine biofouling on recreational boats on swing moorings and berths. *Management of Biological Invasions*, *4*(4), 327–341.

Clarke Murray, C., Pakhomov, E. A., & Therriault, T. W. (2011). Recreational boating: a large unregulated vector transporting marine invasive species. *Diversity and Distributions*, *17*(6), 1161–1172.

Clarke Murray, C., Therriault, T. W., & Pakhomov, E. (2013). What lies beneath? An evaluation of rapid assessment tools for management of hull fouling. *Environmental Management*, *52*(2), 374–384.

Cole, E., Keller, R. P., & Garbach, K. (2019). Risk of invasive species spread by recreational boaters remains high despite widespread adoption of conservation behaviors. *Journal of Environmental Management,* 229, 112–119.

Cunningham, S., Teirney, L., Brunton, J., McLeod, R., Bowman, R., Richards, D., Kinsey, R., & Matthews, F. (2019). Mitigating the threat of invasive marine species to Fiordland: New Zealand's first pathway management plan. *Management of Biological Invasions*, *10*(4), 690–708.

Davidson, I. C., Brown, C. W., Sytsma, M. D., & Ruiz, G. M. (2009). The role of containerships as transfer mechanisms of marine biofouling species. *Biofouling*, *25*(7), 645–655.

Davidson, I. C., Scianni, C., Minton, M. S., & Ruiz, G. M. (2018). A history of ship specialization and consequences for marine invasions, management and policy. *Journal of Applied Ecology*, *55*(4), 1799–1811.

Davidson, I. C., Zabin, C. J., Chang, A. L., Brown, C. W., Sytsma, M. D., & Ruiz, G. M. (2010). Recreational boats as potential vectors of marine organisms at an invasion hotspot. *Aquatic Biology*, *11*(2), 179–191.

Davidson, I., Floerl, O., Cunningham, S., & Edhouse, S. (2021). Report on Level of Fouling Project Part A. Prepared for Auckland Council, Auckland, New Zealand.

Davidson, I., Floerl, O., Fletcher, L., & Cahill, P. (2019). *Level of fouling rank scale – an updated guideline*. Prepared for Auckland Council, Auckland, New Zealand.

Department of Conservation (2017) *Regional Coastal Plan: Kermadec and Subantarctic Islands*. New Zealand Department of Conservation, Wellington, New Zealand.

Floerl, O. (2004). *Protocol to quantify the Level of Fouling (LOF) on vessel hulls using an ordinal rank scale*. Prepared by NIWA Ltd. for the New Zealand Ministry of Fisheries.

Floerl, O., & Coutts, A. D. M. (2011). Feasibility of using remote-operated vehicles (ROVs) for vessel biofouling inspections. Prepared for Western Australia Department of Fisheries. *Fisheries Occasional Publication*, *117*, 54.

Floerl, O., & Inglis, G. J. (2005). Starting the invasion pathway: the interaction between source populations and human transport vectors. *Biological invasions*, *7*(4), 589–606.

Floerl, O., Inglis, G. J., & Hayden, B. J. (2005). A risk-based predictive tool to prevent accidental introductions of nonindigenous marine species. *Environmental management*, *35*(6), 765–778.

Floerl, O., Smith, M., Inglis, G., Davey, N., Seaward, K., Johnston, O., Fitridge, I., Rush, N., Middleton, C., & Coutts, A. (2008) Vessel biofouling as a vector for the introduction of non-indigenous marine species to New Zealand: Recreational yachts. Report to Biosecurity New Zealand, Ministry of Agriculture and Fisheries, Wellington, New Zealand.

Forrest, B. (2014). *Vessel hull fouling as a marine biosecurity indicator in the Top of the South: 2014 survey*. Top of the South Marine Biosecurity Partnership, Technical Report 2014/01.

Forrest, B. (2016). *Regional recreational vessel hull fouling survey and boater questionnaire.* Technical Report 2016/01. Top of the South Marine Biosecurity Partnership.

Forrest, B. (2017). *Vessel hard-stand survey and biofouling risk factors*. Top of the South Marine Biosecurity Partnership Technical Report 2017/02.

Foster, V., Giesler, R. J., Wilson, A., Nall, C. R., & Cook, E. J. (2016). Identifying the physical features of marina infrastructure associated with the presence of non-native species in the UK. *Marine Biology*, *163*(8), 1–14.

Hopkins, G. A., & Forrest, B. M. (2010). A preliminary assessment of biofouling and non-indigenous marine species associated with commercial slow-moving vessels arriving in New Zealand. *Biofouling*, *26*(5), 613–621.

Iacarella, J. C., Burke, L., Davidson, I. C., DiBacco, C., Therriault, T. W., & Dunham, A. (2020). Unwanted networks: Vessel traffic heightens the risk of invasions in marine protected areas. *Biological Conservation*, *245*, 108553.

Iacarella, J. C., Saheed, D., Dunham, A., & Ban, N. C. (2019). Non-native species are a global issue for marine protected areas. *Frontiers in Ecology and the Environment*, *17*(9), 495–501.

Inglis, G.J., Floerl, O., Ahyong, S., Cox, S., Unwin, M., Ponder-Sutton, A., Seaward, K., Kospartov, M., Read, G., Gordon, D., Hosie, A., Nelson, W., d'Archino, R., Bell, A., Kluza, D. (2010) *The biosecurity risks associated with biofouling on international vessels arriving in New Zealand: summary of the patterns and predictors of fouling*.

Biosecurity New Zealand Technical Paper No: 2008. Report prepared for MAF Biosecurity New Zealand Policy and Risk Directorate Project FP0811321 No. 182.

Johnson, L. E., Ricciardi, A., & Carlton, J. T. (2001). Overland dispersal of aquatic invasive species: a risk assessment of transient recreational boating. *Ecological Applications*, *11*(6), 1789–1799.

Kelly, N. E., Wantola, K., Weisz, E., & Yan, N. D. (2013). Recreational boats as a vector of secondary spread for aquatic invasive species and native crustacean zooplankton. *Biological Invasions*, *15*(3), 509–519.

Leonard, J. (2009). *Hull fouling surveys of recreational boats in Hawaii*. Report for the Division of Aquatic Resources, Honolulu, Hawaii, USA.

Lough, R. S. (2009). *The current state of rabbit management in New Zealand: Issues, options, and recommendations for the future*. Contract report for MAF Biosecurity New Zealand, Wellington, New Zealand.

Magurran, A. E. (2004). *Measuring biological diversity*. Blackwell Publishing.

Miller, A. W., Davidson, I. C., Minton, M. S., Steves, B., Moser, C. S., Drake, L. A., & Ruiz, G. M. (2018). Evaluation of wetted surface area of commercial ships as biofouling habitat flux to the United States. *Biological Invasions*, *20*(8), 1977–1990.

Minchin, D., Floerl, O., Savini, D., & Occhipinti-Ambrogi, A. (2006). Small craft and the spread of exotic species. In *The ecology of transportation: managing mobility for the environment* (pp. 99–118). Springer, Dordrecht.

Moser, C. S., Wier, T. P., First, M. R., Grant, J. F., Riley, S. C., Robbins-Wamsley, S. H., Tamburri, M. N., Ruiz, G. M., Miller, A. W., & Drake, L. A. (2017). Quantifying the extent of niche areas in the global fleet of commercial ships: the potential for 'super-hot spots' of biofouling. *Biological Invasions*, *19* (6), 1745–1759.

Moser, C. S., Wier, T. P., Grant, J. F., First, M. R., Tamburri, M. N., Ruiz, G. M., Miller, A. W., & Drake, L. A. (2016). Quantifying the total wetted surface area of the world fleet: a first step in determining the potential extent of ships' biofouling. *Biological Invasions*, *18*(1), 265–277.

[NPCA] National Pest Control Agencies. (2020). *Pest rabbits – monitoring and control good practice guidelines*. Bionet and National Pest Control Agencies, Ministry for Primary Industries, Wellington, New Zealand.

Peters, K., Sink, K., & Robinson, T. B. (2019). Aliens cruising in: explaining alien fouling macro-invertebrate species numbers on recreational yachts. *Ocean & Coastal Management*, *182*, 104986.

Rothlisberger, J. D., Chadderton, W. L., McNulty, J., & Lodge, D. M. (2010). Aquatic invasive species transport via trailered boats: what is being moved, who is moving it, and what can be done. *Fisheries*, *35*(3), 121–132.

Ruiz, G. M., Freestone, A. L., Fofonoff, P. W., & Simkanin, C. (2009). Habitat distribution and heterogeneity in marine invasion dynamics: the importance of hard substrate and artificial structure. In *Marine hard bottom communities* (pp. 321–332). Springer, Berlin, Heidelberg.

Ulman, A., Ferrario, J., Forcada, A., Seebens, H., Arvanitidis, C., Occhipinti-Ambrogi, A., & Marchini, A. (2019). Alien species spreading via biofouling on recreational vessels in the Mediterranean Sea. *Journal of Applied Ecology*, *56*(12), 2620–2629.

Weigelt, P., Denelle, P., Brambach, F. & Kreft, H. (2021) A flexible R package with Shiny app to practice plant identification for online teaching and beyond. *Plants, People, Planet*, 4(2), 122–127.

Wikum, D. A., & Shanholtzer, G. F. (1978). Application of the Braun-Blanquet cover-abundance scale for vegetation analysis in land development studies. *Environmental Management*, *2*(4), 323–329.

Zabin, C. J., Ashton, G. V., Brown, C. W., Davidson, I. C., Sytsma, M. D., & Ruiz, G. M. (2014). Small boats provide connectivity for nonindigenous marine species between a highly invaded international port and nearby coastal harbors. *Management of Biological Invasions*, *5*(2), 97.

Zabin, C., Davidson, I., Holzer, K., Smith, G., Ashton, G., Tamburri, M., & Ruiz, G. (2018). How will vessels be inspected to meet emerging biofouling regulations for the prevention of marine invasions? *Management of Biological Invasions*, *9*(3), 195–208.

9. APPENDICES

APPENDIX 1. WORKSHOP AND TRAINING

Project workshop

On 20 June 2022 a full-day project workshop was held at Auckland Council's Manukau offices. It was attended by 17 marine biosecurity and technical diving specialists from:

- Auckland Council,
- Bay of Plenty Regional Council,
- Northland Regional Council,
- Marlborough District Council,
- Top of the South Marine Biosecurity Partnership,
- Environment Southland,
- Ministry for Primary Industries, and
- Marine & Environmental Field Services (Northland).

They included some of Aotearoa New Zealand's most experienced vessel biofouling surveillance teams and users of the LOF scale. The workshop was delivered by biosecurity scientists from Cawthron Institute (the authors of this report).

The workshop agenda covered the following topics and activities:

1. the objectives of the overall project and workshop,
2. the origin and application history of the LOF scale,
3. LOF rank definitions, assumptions and limitations,
4. approaches to *in situ* application of LOF ranks during vessel inspections, including tips to reduce observer bias,
5. use of underwater still and video imagery to discuss approaches to inspections and LOF scoring,
6. group exercises to highlight the importance of accuracy and precision, in particular when the LOF scale is used as a metric for compliance with pathway management initiatives, and
7. a 'tour' through operational and training resources developed during this project, in particular (i) the 'LOF calculator' that generates whole-vessel LOFs on the basis of multiple hull- and niche-area LOF ranks, and (ii) the 'LOF app'.

Key discussions, results, insights and agreements of the workshop are briefly summarised below:

Utility of the LOF scale. While the LOF ranks do not provide the same granularity for biofouling abundance as for example the empirical quantification of percentage cover would, all workshop attendants considered the cost-effectiveness of LOF-based vessel surveillance a key advantage and prefer it to alternatives such as the use of quadrat-based surveys or alternative rank scales, such as the US Navy's 'Fouling Rating'. Some regions have allocated up to 30,000 vessel LOF records and there is no plan to use a different approach. Rather, there are ambitions to develop a centralised resource for access by regional authorities (see Marine Vessel Portal below).

Need for slight modification of LOF rank definitions. The original LOF ranks are defined based on percentage cover ranges and, in some cases, the presence of a single or more visible taxonomic groups. This was done based on usual patterns of community assembly in benthic marine systems. However, all practitioners agreed that there are frequently situations where percentage cover may exceed 40% (the threshold for LOF 5) but where there is only a single taxon visible (e.g. heavy barnacle settlement in some Northland regions), which is not consistent with the LOF 5 definition. There was unanimous support for retaining the critical percentage cover element of the LOF scale but removing aspects related to taxon richness and composition, as has been undertaken in Part A of the LOF project and is described in Section 3 of this report.

The importance of accuracy and precision. The exercises and discussions by workshop participants confirmed the high level of familiarity with the field-based use of the LOF scale, and the awareness of sources of bias. Nevertheless, group scoring exercises using a fixed set of images and footage confirmed a reasonable level of variation in LOF rank allocation among workshop participants (Figure 13). This was not unexpected given the lack of protocols and resources, and confirms the timeliness of the overall project and its outputs.

Ability of LOF app data capture and output to interface with, or be suitable for import into, the **Marine Vessel Portal** (MVP) biofouling surveillance database developed and maintained by the Top of the North Marine Biosecurity Partnership. The MVP is built using the ESRI product platform and is a growing repository of vessel inspection data that currently includes >30,000 records. It is intended for nationwide use eventually, and participants considered it important that the vessel inspection data and LOF ranks facilitated by the LOF app are suited for upload into the MVP. It was agreed that the development of the final version of the LOF app would be undertaken in collaboration with the MVP custodian.

Descriptions and schematics. Workshop participants recommended that several elements be included in the LOF app's methods and training sections: (1) images and descriptions of all parts of recreational vessel hulls, and (2) full 'side view' images of recreational vessels (can be taken on hard stand) with 'photoshopped' distributions of different amounts of biofouling, corresponding to different LOF ranks. Item 1 was readily agreed on. The necessity for item 2 will be considered in the context of similar resources that are being prepared.

LOF aggregation. Attendees generally agreed with our proposition that the collection of multiple hull- and niche-area LOF ranks, and their subsequent systematic aggregation to a whole-vessel LOF, is the most rigorous approach for biofouling surveys since it is easiest to allocate LOFs to small and 'manageable' areas rather than submerged hulls in their entirety. Still, some participants expressed preference for a middle-of-the-road approach where inspectors collect only three LOFs for subsequent aggregation. It was therefore decided that the final version of the LOF app will enable users to calculate a whole-vessel LOF from: (1) all hull- and niche-area LOFs (see sections above), or (2) three broad LOF groups (hull; keel; running gear / niche areas). Direct entry of a whole-boat LOF rank in the field will also be embedded in the app data entry component.

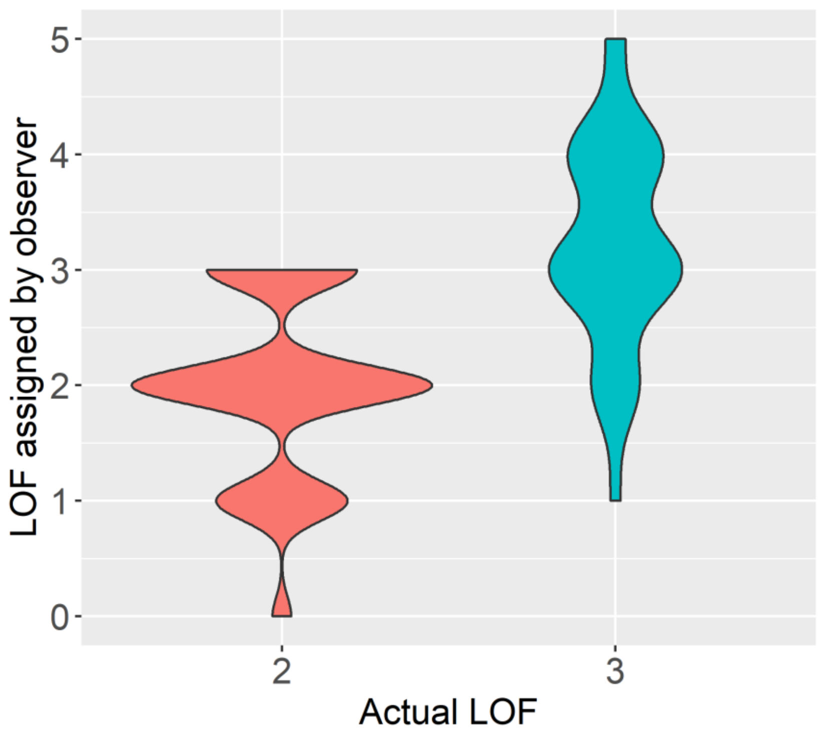


Figure 13. Violin plot of LOF ranks allocated to the same two images by 17 workshop participants. In orange: frequency distribution of LOF ranks allocated to an image that contained a validated LOF 2 scenario. The horizontal width of the distribution indicates the relative frequency with which workshop participants scored the image. In this case, most participants scored the correct LOF rank (plot is widest at LOF 2), but a reasonable proportion scored it a LOF 3, LOF 1 or even LOF 0. In turquoise: frequency distribution of LOF ranks allocated to an image that contained a validated LOF 3 scenario. While the correct rank (LOF 3) had the highest relative frequency of scores, some participants thought the image represented an LOF 1, LOF 2, LOF 4 or even LOF 5 scenario.

Avenues for LOF training

Accuracy and precision in the use of the LOF scale by operational biosecurity teams requires the development and maintenance of relevant skills. While our workshop confirmed a high level of LOF expertise and experience among the regional teams that attended, there was an indication that regular group activities aimed at identifying and addressing variation within and between teams would be beneficial. And, of course, when new personnel join existing teams, it is important to ensure that they are provided with adequate LOF training opportunities.

Table A1.1 contains suggestions for how new and existing LOF practitioners can acquire, monitor and maintain their LOF skills base, and how observer bias within and between regional teams can be quantified and minimised. The descriptions are deliberately kept high level, the intention being that they describe the objectives and approximate approaches for different activities. Step-by-step guidelines for developing and implementing the activities can easily be prepared in correspondence to team sizes, experience levels, and for in-house vs multi-region activities.

Table A1.1. Activities for development and maintenance of LOF skills used in vessel biofouling surveillance programmes.

Objective	Recommended activities
Familiarisation of new personnel with LOF scale and implementation	1. Sufficient time allocated to enable working through all resources prepared by the LOF project and described in this report.
	2. Accompany experienced personnel on vessel inspections. Sufficient time dedicated to discussion of LOF rank allocations until proficiency is increasingly apparent.
Maintaining or improving observer accuracy	1. Regular use of the self-evaluation feature in the LOF app. Tracking of success rates until plateau observed. From then on less-frequent use (or as needed) to maintain accuracy levels.
	2. It is also possible to collate video footage of inspections that resulted in validated LOF ranks, and to provide these for practitioners to assess and maintain their ability to accurately score LOFs.
Assessing and fostering within-team consistency	1. Establishment of an annual or biannual 'team day' where members from the same regional surveillance team allocate LOFs to validated still or video imagery, and analyse the outcomes. Ideally this should involve at least five individual vessels containing hull and niche areas that extend across the entire LOF scale. Simple summaries can be developed to illustrate variation between team members. Where there is variation, use discussions to establish the cause and ensure that 'outliers' have access to training materials and opportunities. Repetition of the exercise should result in decreased levels of variation. When this is not the case, additional and more frequent training activities need to be developed and implemented.
	2. The exercises described above can also be undertaken in-water or via a visit to a hard-stand facility. Options there include (i) the assessment of vessels that have previously (and not by members of the team undertaking the activity) been inspected and their LOF ranks validated using objective and empirical methods, or (ii) the use of clean vessels to which known quantities and distributions of 'mock biofouling organisms' have been attached using magnets or adhesives.
Assessing and fostering between-team consistency	The activities described for addressing within-team consistency can also be undertaken together with other teams (e.g. from other jurisdictions). This enables the measurement of regional consistency and precision with regard to biofouling inspections using the LOF rank scale.

APPENDIX 2. THE MODIFIED MCLEAN SCALE OF RABBIT INFESTATION

The modified McLean scale, 2012 version. Reproduced from NPCA (2020).

1	No sign found. No rabbits seen.
2	Very infrequent sign present. Unlikely to see rabbits.
3	Pellet heaps spaced 10m or more apart on average. Odd rabbits seen; sign and some pellet heaps showing up.
4	Pellet heaps spaced between 5 m and 10 m apart on average. Pockets of rabbits; sign and fresh burrows very noticeable.
5	Pellet heaps spaced 5 m or less apart on average. Infestation spreading out from heavy pockets
6	Sign very frequent with pellet heaps often less than 5m apart over the whole area. Rabbits may be seen over the whole area.
7	Sign very frequent with 2-3 pellet heaps often less than 5 m apart over the whole area. Rabbits may be seen in large numbers over the whole area.
8	Sign very frequent with 3 or more pellet heaps often less than 5 m apart over the whole area. Rabbits likely to be seen in large numbers over the whole area.