INTRODUCTION

Aquaculture is the fastest growing marine sector globally, and it promises to contribute significantly to future food and energy security. Algae, including seaweeds (macroalgae), form >20% of total aquaculture production biomass, and algal cultivation is growing rapidly compared with other farmed species (approximately 8% yr\(^{-1}\)) following the growth and diversification in global markets for algal or macroalgal products. Beyond the direct commercial value of macroalgal products, the responsible expansion of macroalgal cultivation promises to contribute significantly towards future food and energy security, sustainable livelihoods, ecosystem services and habitat provisioning for a range of associated organisms globally. Habitat provisioning underpins biodiversity and ecosystem structure and functioning, supports many ecosystem services and has possible benefits to other marine industries, including enhancement of commercial fish stocks. In macroalgal cultivation, however, only recently has habitat provisioning started to be assessed at a local scale (within a farm’s footprint) and with a range of different approaches. This review evaluates techniques used to quantify habitat provisioning in and around macroalgal cultivation sites, for species ranging from microorganisms to megafauna, and outlines recommendations to enable a more comprehensive ecological valuation of macroalgal cultivation in the future. The majority of information on biodiversity associated with macroalgal cultivation is associated with quantifying biofouling or pest organisms, rather than the contribution of colonising species to healthy ecosystem functioning. We suggest how better monitoring of macroalgal cultivation could enable an ecosystem approach to aquaculture (EAA) in the future. To achieve this, we highlight the need for standardised and robust methods for quantifying habitat provisioning that will enable assessment and monitoring of macroalgal cultivation sites of varying scales and within different regions and environmental settings. Increased evidence for the potential habitat value of macroalgal cultivation sites will help inform and shape marine legislation, licencing and certification for macroalgal farmers and potentially reduce marine user conflicts, helping the industry to continue to grow sustainably using EAA.
could provide environmental benefits, which have been detailed alongside potential negative impacts in several recent reviews5–13 (summarised in Figure 1). Many of these environmental effects relate to key ecosystem services (ESs) including climate regulation, storm protection, biogeochemical cycling and provisioning of food and habitat, or refugia to support secondary production for wild capture fisheries6,14–17 (Figure 1). The proposed ESs enhanced by macroalgal cultivation would support several UN sustainable development goals including: contributing to global health and well-being; providing economic growth and resilience in coastal communities; enabling responsible consumption and production; facilitating climate action and benefiting marine ecosystems.18

Habitat provisioning is a hugely important ecological process that underpins biodiversity, ecosystem structure and function, and
supports many ESs such as food provisioning, water quality, maintenance of pest and disease control and recreation and ecotourism.\textsuperscript{19} Habitat provisioning is included differently under prominent ES classification systems, and they are (1) maintaining habitats and nursery populations\textsuperscript{20}; (2) refugia, or nursery and migration habitat\textsuperscript{21}; (3) habitat heterogeneity\textsuperscript{22}; and (4) life cycle maintenance – nursery service.\textsuperscript{23,24} This broad range of terminology makes defining and quantifying the value of habitat provisioning difficult, with vague metrics in place to do so.\textsuperscript{25} Furthermore, as shown in Figure 1, there may be complex interactions between species, which are difficult to separate and monitor. In the broadest sense, habitat provisioning will vary based on abiotic conditions, farm location or farm type. For example, an offshore kelp farm in Europe will provide a very different potential habitat to a shallow-bottom echeumatoid farm in Southeast Asia. All macroalgal cultivation sites, however, present their own challenges for monitoring habitat provisioning, which has until now limited their study.\textsuperscript{17}

Quantifying the habitat provided by macroalgal cultivation has received little attention, and therefore, no economic or ecological valuations of this potential benefit have yet been made.\textsuperscript{16,17,25} In a recent review evaluating the available literature on the habitat value of bivalve and macroalgal cultivation of the 65 studies identified, only eight of these included macroalgal cultivation sites.\textsuperscript{17} This review also only included the habitat value of aquaculture sites for wild macroinvertebrate and fish populations because of a lack of information on how macroalgae cultivation affects other species\textsuperscript{17} (e.g. microorganisms, marine mammals or seabirds etc.). Macroalgal cultivation can, however, provide habitat for a diverse array of fauna and flora, similar to that of wild macroalgal populations,\textsuperscript{26} through the provision of novel suspended and benthic three-dimensional substrates, food and enhanced reproduction and recruitment opportunities.\textsuperscript{5,7,13,17} This in turn could potentially support secondary food production with spill-over benefits for fisheries.\textsuperscript{16,17} It is unclear, however, how effective temporary habitats of seasonal macroalgal cultivation sites would be at maintaining biodiversity after harvests and the removal of macroalgal biomass. It is also unclear whether sites will simply aggregate wild populations instead of enhancing overall population size, production and viability through reproduction and juvenile recruitment.\textsuperscript{5,7,16,17} Further issues relate to which species macroalgal farms will support, and whether these will differ from surrounding areas, thus potentially altering ecosystem dynamics or introducing invasive species.\textsuperscript{27} Better monitoring of species at macroalgal cultivation sites is therefore needed to address these concerns and determine whether this form of aquaculture supports habitat provisioning while quantifying what its ecological (and economic) value may be.

Increased recognition and valuation of the habitat provisioned by macroalgal cultivation would enable better farm design and management to optimise potential environmental benefits, mitigate potential negative impacts and contribute towards sustainable development and an ecosystem approach to aquaculture (EAA).\textsuperscript{8,16,25,28} EAA aims to design and integrate aquaculture within ecosystems to promote sustainable development, equity and ecosystem resilience while minimising any potential negative impacts.\textsuperscript{29,30} In macroalgal cultivation, EAA may guide policy, financing and certification schemes towards promoting increased sustainable practices in mariculture development.\textsuperscript{11} Accordingly, there is the potential for macroalgal aquaculture to lead the way as an example of sustainable EAA; however, more quantitative evidence on a wider range of the potential environmental benefits is needed, including habitat provisioning.\textsuperscript{25}

This review aims to: (1) summarise evidence relating to how macroalgal cultivation could provision habitat for species spanning from microorganisms to megafauna, and (2) generate recommendations for standardised monitoring of habitat provisioning in and around macroalgal cultivation sites for these species. In turn, this could support the development and optimisation of practices for EAA, which will enable the ecological and economic value of macroalgal aquaculture to be assessed more holistically and help to inform its legislation and regulation in future. Where information on macroalgal cultivation is lacking, we draw upon some relevant studies from wild macroalgae populations and shellfish/finfish aquaculture to help guide in developing universal standardised monitoring techniques. Adopting this approach, we also hope to seek ways of standardising the monitoring of habitat provisioning between aquaculture species, which will be particularly useful given the increasing implementation of integrated multitrophic aquaculture (IMTA) systems.

## 2 | POTENTIAL HABITAT PROVISIONING OF MACROALGAL CULTIVATION FOR DIFFERENT TAXONOMIC AND FUNCTIONAL GROUPS AND METHODS ENABLING ITS QUANTIFICATION

As Figure 1 illustrates, complex interactions exist in macroalgal cultivation sites between species and between species and the environment, which will differ depending on farm scale, location and type (discussed further in Section 3). These complexities are more explicitly detailed in other recent reviews (e.g. Refs. 10,17), and in this section, we outline some of the ways macroalgal cultivation may affect different taxonomic and functional groups based on previous studies, why they are important to quantify and challenges relating to monitoring. We have grouped organisms based on their taxonomic and functional groups, how they inhabit or interact with macroalgal cultivation sites, and their monitoring requirements.

### 2.1 | Microorganisms (Bacteria, viruses, archaea, fungi, oomycetes and protists)

Bacteria, viruses, archaea, fungi, oomycetes (fungus-like eukaryotic water moulds) and protists are often overlooked in habitat evaluations and biodiversity assessments in aquaculture, despite their importance in maintaining ecosystem health and functioning through nutrient and carbon cycling, decomposing organic matter and helping prevent diseases or harmful algal blooms (HABs).\textsuperscript{31–35}
Macroalgae host diverse associations of microorganisms that facilitate the health and function of the host plants, such as morphological development, disease protection and antifouling properties from epibionts (see Section 4). As such, macroalgae and their microbiomes should be considered as synergistic ecological units or holobionts. Additionally, the microorganisms associated with macroalgae are often sources of novel compounds that have industrial applications, for example, bacteria hosted on Eucheuma species produce enzymes that could be used in biofuel production. However, changes in the microbiome structure and bacterial infections may also contribute to several diseases (summarised in Ref. 40), including ice–ice rotting syndrome, which has been known to decimate entire *Kappaphycus* and *Eucheuma* seaweed farms, causing significant economic losses. Oomycete pathogens can also be responsible for extensive damage, as seen in Korean *Pyropia* seaweed farms, and are more diverse and geographically widespread than currently acknowledged, posing threats to macroalgal cultivation in Asia and Europe. The presence of harmful microorganisms and diseases at macroalgal cultivation sites also pose the risks of spreading to neighbouring wild macroalgal populations, with the potential to cause substantial ecological damage. A greater understanding of the microbiome of macroalgal cultivation is therefore needed to determine both its ecological value in macroalgal cultivation, and understand how the macroalgal microbiome is regulated by other associated biodiversity present at cultivation sites, which may mitigate disease outbreaks. Macroalgal cultivation sites may also potentially affect microorganisms in the water column and benthic sediments, through production of soluble dissolved and particulate organic matter, deposition of detritus and the potential attraction of waste-producing species such as fish (Figure 1). Microorganisms in the surrounding environment, however, are unlikely to be affected to the extent seen in other aquaculture species, particularly fish farms, as waste production is comparatively low (although less is known about the amounts produced at larger offshore sites). Determining interactions between macroalgal cultivation sites and microbial communities in the water column and benthos will be an important step in future research, given that microorganisms can act as powerful indicators monitoring ecosystem health. Relatively little research has been conducted so far to investigate this.

Microorganisms can be quantified either from the surface of the macroalgae or from water or sediment samples in macroalgal cultivation sites, which can host distinct microbiomes from one another. The diversity and community composition of microorganisms, such as fungi, can vary between tissue types (e.g. stipe, holdfasts and blades) of the same macroalgae, so multiple samples from individuals should be collected to accurately capture their microbial diversity. Various methods can be used for microorganism quantification (Table 1), including microscopy, cell counts and RNA or DNA sequencing methods. The main constraints for quantifying macroalgal farm microbiomes, however, are generally a lack of knowledge of the microbial ecology of these systems and because currently many are not culturable by common microbial methods; however, the advancement of molecular methods may help to mitigate these issues (Table 1). Additionally, eukaryotic microorganisms, including protists, are especially understudied within the seaweed holobiont, so particular focus needs to be more directed on determining their importance. If sampling effort of microorganisms in wild and cultivated macroalgal populations was increased, reference libraries should be compiled to make detecting and quantifying their abundance easier in future. It should also be recognised that better understanding of the dynamics and plasticity of these microbial communities is needed, as there will be similarities in their ecological and functional roles within ecosystems.

### 2.2 | Plankton (pico to macro)

Plankton provide important primary food sources in marine food webs, and regulate nutrient, carbon and oxygen cycles in the oceans. Therefore, plankton abundance and diversity are important measures of ecosystem productivity and health. Macroalgal cultivation sites may provide zooplankton with shelter and food; however, plankton may also negatively affect cultivated macroalgae. For example, ‘diatom felt’ caused by settling diatoms has been shown to result in algal bleaching and significant economic losses for farmers in *Pyropia* farms in Korea. Macroalgal cultivation sites may also benefit overall ecosystem health by mitigating eutrophication and harmful algal blooms (HABs) through improving water quality, stabilising the water column and assimilating excess nutrients (Figure 1). The installation of macroalgal farms in China has been observed to alleviate eutrophication and ocean acidification, reduce turbidity and subsequently enhance phytoplankton diversity and biomass. As primary producers, however, macroalgae and phytoplankton may compete for light and nutrients, particularly at large-scale cultivation sites (>50 lines × 200 m) or those with high macroalgal biomass density, like that in Sanggou Bay, China. This competition in turn may reduce food availability for wild fish or shellfish populations and affect fisheries or shellfish production. Farms should be sited in suitable locations with sufficient nutrient concentrations and tidal mixing, and therefore with adequate environmental carrying capacity (the maximum biomass of a farmed species that can be supported without exceeding the maximum acceptable impacts to the farmed stock and its environment) (see Section 3.5). Indeed, no significant changes in plankton were predicted or detected in models of hydrodynamic and biogeochemical processes in United Kingdom and Dutch small- or large-scale macroalgal farms. Thus, the effects of macroalgal cultivation on plankton assemblages are site-specific.
### Table 1: List of suitable monitoring techniques to assess habitat provisioning in macroalgal cultivation sites for different taxonomic and functional groups. Potential pros and cons for each technique are discussed with recommendations for improved use and examples of previous usage in macroalgal cultivation sites and other similar habitats.

<table>
<thead>
<tr>
<th>Monitoring technique &amp; species groups it can be used for</th>
<th>Pros (+) and cons (-) for use in macroalgal cultivation sites to assess habitat provisioning</th>
<th>Recommendations for future use</th>
<th>Example uses in macroalgae (M), finfish (F), shellfish (S) aquaculture, wild macroalgal populations (W) or other (O)</th>
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<tr>
<td>Water sampling, plankton nets or trawls Microorganisms and plankton</td>
<td>Inexpensive, simple and highly replicable (+) Species can then be identified by several methods e.g.: - Microscopy – time-consuming and requires taxonomic expertise, but captures total biodiversity at a given time point (-/+/-) - Fluorescence microscopy – a fast and direct detection protocol for microorganisms (+) - Fluorometry – rapidly measures chlorophyll a concentrations as proxies for productivity and phytoplankton biomass (+). Does not identify species or detect zooplankton species(-) - Automated or semi-automated systems for quantifying plankton e.g. flow cytometry or FlowCAM (see Refs. 68,161,162) – faster but require established reference libraries or taxonomic expertise (+/-) - Molecular methods (see below) – faster but require established reference libraries that are currently lacking (+/-)</td>
<td>Should standardise depth and volume of samples, mesh size of nets, time of day and year of surveying, number of replicates taken and post-analysis methods for identification and enumeration of species Should create reference libraries of microorganism and plankton DNA or RNA in cultivation sites and wild populations to aid future quantification34</td>
<td>Microorganisms (reviews): e.g. Refs. 34 (M); 35,56 (F); 38 (W &amp; O) Plankton: e.g. Refs. 68,76,120,163 (M); 164 (S, F &amp; M); 165 (S); 161,162 (O)</td>
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<td>Sediment and light traps Microorganisms, plankton, pelagic invertebrates, fish and decapod larvae</td>
<td>Sediment traps are deployed on the seabed and can collect plankton over longer time periods (e.g. monthly) for a more representative diversity (+) Sediment traps are not suitable for offshore farms due to depth limitations of setting up traps (-) Light traps can be deployed in the water column at night to collect species with nocturnal migration patterns, including amphipods and other major epibiont species that would otherwise not be present during the day166 (+) Both are low-cost and have similar post-analysis methods used to water sampling methods (above)</td>
<td>Should set traps at fixed depths from the seabed or in the water column within the farm and at reference areas ahead of typical seasonal or predicted plankton blooms Timing and duration of light trap deployment should be recorded for standardisation, along with environmental conditions. Concurrent plankton trawls should be conducted to determine sampling bias166</td>
<td>Microorganisms: e.g. Ref. 167 (F) Plankton: e.g. Ref. 168 (M) Pelagic invertebrates, fish and decapod larvae: e.g. Ref. 166 (F)</td>
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<td>Autonomous detection systems Microorganisms and plankton</td>
<td>Deployable in situ for continuous plankton monitoring and instantaneous harmful algal bloom (HAB) alerts75 but does not quantify total community assemblages (+/-) Currently further development is needed before real-time microorganism detection systems are available,169 but portable sensors and combined modelling methods may aid in development (-/+/-) Commercial monitoring systems are expensive for small-scale farmers, but low-cost options are being developed (e.g. Refs. 170,171) (-/-) Requires good connectivity for instantaneous data transfer i.e. 4G networks, which may not be available in all farm locations (-)</td>
<td>Should standardise sensors used and their placement on farms Should invest further research and development into these systems to streamline data connectivity and lower production and running costs for use in small-scale farms Should ensure systems are simple to use for operation and maintenance by farmers</td>
<td>Microorganisms: e.g. Refs. 172 (O); 169 (review) Plankton: e.g. Refs. 170,171 (S)</td>
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**TABLE 1** (Continued)

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<tr>
<td>Collecting species on macroalgal biomass Microorganisms and epibionts</td>
<td>Easy to collect samples on farm maintenance or harvest trips (+) Species can be then identified by several methods e.g.: • Microscopy or by eye – time-consuming and requires taxonomic expertise, but captures total biodiversity at a given time point above a visible size class (−/+) • Molecular methods (see below) – faster but requires established reference libraries (+/−) • Photographic analysis (e.g., using ImageJ or equivalent software) – standardises measurements for sessile epibionts, but excludes less abundant mobile species, and those obscured in holdfasts (+/−)</td>
<td>Should standardise methods for collection, preservation, species identification and enumeration</td>
<td>Microorganisms: e.g., Refs 55,174–177 (W) Epibionts: e.g., Refs 88,101-105 (M);83,173,178,179 (W)</td>
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<td>Benthic sediment grabs or diver collected cores Benthic microorganisms and infauna</td>
<td>Routinely practised in marine ecology so techniques are relatively standardised180 (+) Constrained by depth and substrate type, e.g., sampling offshore farms or those suspended over bedrock is challenging (−) Species can be then identified via: • Taxonomy – expensive, time-consuming and requires expertise (−) • Molecular methods (see below) – faster but requires established reference libraries (+/−)</td>
<td>Should conduct pre-surveys via side-scan sonar or drop-down cameras to determine substrate types and any vulnerable or protected habitats to be avoided$^6$ Should use standardised monitoring methods, e.g., Refs. 181,182, and diverse biotic indices and statistical approaches (e.g., Refs. 117,183)</td>
<td>Benthic microorganisms: e.g., Refs. 184–186 (F) Benthic infauna: e.g., Refs. 100,101,118,120,121 (M); 184 (F)</td>
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<td>Small beam trawls Benthic epifauna</td>
<td>Routinely conducted and replicable around different benthic sites and effective at assessing total community assemblages (+) Relatively destructive and may be hard to conduct around farm infrastructure or directly below farms (−) High levels of settled farm detritus may clog nets and hinder accurate quantification of epifauna (−) Can subsequently determine biometrics, age/size and gut contents of epifauna (+)</td>
<td>Should standardise methods (e.g., tow size, net size, tow length and duration, sample preservation, species identification and enumeration). Where trawl sizes differ, data should be standardised by area/volume Static sampling methods (e.g., trap or camera surveys) are more appropriate around aquaculture infrastructure</td>
<td>Benthic epifauna: e.g., Refs. 187 (S); 188 (F); 180 (O)</td>
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<td>Traps or nets Benthic epifauna and finfish</td>
<td>Relatively simple to deploy below or around cultivation sites for crustaceans and fish species (e.g., Ref. 101) (+) Traps may be particularly effective for surveying species of commercial importance, but will be biased for certain species (+/−) Can subsequently determine biometrics, age/size and gut contents of caught individuals or tag them (see mark recapture or biologging below) (+)</td>
<td>Should be used with other survey methods to derive whole-site biodiversity Should standardise methods (e.g., net or trap size, length of deployment, baited or unbaited). Where length of deployment differs among studies, data should be standardised to catch per hour</td>
<td>Benthic epifauna: e.g., Refs. 101 (M); 187 (S) Finfish: e.g., Refs. 129 (M); 187,189 (S); 130 (S, F &amp; O)</td>
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| Diver/snorkelling surveys using visual counts or handheld cameras Epibionts, benthic epifauna, finfish, mammals, reptiles and seabirds | Non-extractive, routinely conducted and replicable around benthic and pelagic sites (+)  
Can bias towards counting conspicuous and abundant species over cryptic or rare individuals that may be hard to spot within macroalgal farms (−)  
May only capture species a set time point or time of day e.g. does not account for diurnal movements of organisms (−)  
Not suitable for benthic surveys in offshore farms that may be beyond diving depth limits (−)  
Divers presence may cause additional disturbance to mobile species affecting counts (−) | Should standardise methods for surveys e.g. either point counts, transect lengths and widths or manta tows etc. and describe search effort and time of day  
Should use cameras where possible to increase replicability and reduce individual observer bias (see remotely operated camera surveys below) | Benthic epifauna: e.g. Refs. 125 (S); 124,190 (F); 191-193 (O)  
Finfish: e.g. Refs. 75,135 (M); 194 (S); 27,131,195-203 (F); 204,205 (O)  
General reviews of method: e.g. Ref 206 |
| Remotely operated camera surveys (below surface) Epibionts, benthic epifauna, finfish, marine mammals, reptiles and seabirds | Efficient, non-extractive, relatively inexpensive and highly replicable (±)  
Easy to use around farm infrastructure, in high energy environments and varied depths, including offshore systems (±), but dependent on weather, sea state and visibility (−)  
Surveys multiple species and their size classes simultaneously (+), but biased towards larger, more conspicuous individuals over smaller, or cryptic ones that may be obscured by macroalgae or present in holdfasts (±). Can be baited to attract fauna, but this introduces bias (−)  
Different camera specifications and post-analysis techniques affect estimates of species richness, density, cover and assemblage composition (−)  
Post-analysis is time-consuming, but can be streamlined using motion detection software and machine learning (e.g. Refs. 209,213) (±), although this may be ineffective in seaweed farms that are in constant motion (±/−) | Should create standardised monitoring protocols (e.g. describing camera specifications, set-up and deployment, baited or unbaited systems, duration and time of day for deployment, etc.) and video analysis guidelines to limit observer bias between studies.  
Should be used in combination with other monitoring methods to detect cryptic or hidden species | Epibionts: e.g. Ref. 213 (O)  
Benthic epifauna: e.g. Refs. 126,214,215 (F); 191,193,210,216 (O)  
Finfish: e.g. Refs. 208 (M); 209 (S); 217,218 (F); 211 (W)  
General reviews of method: e.g. Refs. 134,206,207,219 |
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| Aerial or drone surveys  
Finfish, marine mammals, reptiles and seabirds | Similar to remotely operated camera surveys (above), but can cover a wider area to facilitate monitoring low-density populations of large species (+)  
Restricted to near-surface species e.g. mammals, birds, reptiles and planktonic elasmobranchs, and may cause disturbance or be unsuitable near seabird colonies (−)  
May be obscured by dense macroalgal biomass, glare and seabed bottom type (−)  
Aerial surveys with planes are expensive (−), but lower cost drone surveys are increasingly common (+), however still requires a licensed drone pilot (−)  
Can simultaneously monitor crop production and success for farmers | Similar recommendations to remotely operated camera surveys (above) in terms of developing standardised protocols, camera specifics and video analysis techniques. Should be used in combination with other monitoring methods to detect non-surfacing or smaller species | Finfish: e.g. Ref. 221 (F)  
Marine mammals, reptiles and seabirds: e.g. Refs 222-225 (F); 226,227 (O)  
Using drones around macroalgal cultivation sites in general: e.g. Refs. 220,228 |
| Tagging or biologging/telemetry  
Benthic epifauna, finfish, marine mammals, reptiles and seabirds | Monitors site fidelity, behaviour of tagged individuals (i.e. use of macroalgal farms as foraging, breeding or nursery grounds) and spill-over effects, to determine whether farms facilitate species recruitment or affect migration patterns (e.g. Refs. 149,189,229) (+)  
Relies on capturing individuals using traps, nets, trawls etc. and can be invasive, expensive and technical if using electronic tags, requiring specialist knowledge and permits, which may not be suitable for small-scale farmers (−) | Should be used in combination with other methods to determine abundance and diversity of species. Should adhere to tagging and ethical guidelines to limit harm to tagged individuals (e.g. Refs. 230,231) | Benthic epifauna: e.g. Refs. 232 (S); 233 (O)  
Finfish: e.g. Refs. 189 (S); 229,234 (F)  
Mammals, reptiles and seabirds & reviews of method: e.g. Refs. 236–238 |
| Acoustic surveys: echosounders, hydrophones or passive acoustic monitoring  
Benthic epifauna, finfish and marine mammals | Efficient, non-extractive, inexpensive and replicable (+)  
Echosounders can detect morphological, geographical and behavioural data of fish around cultivation lines (+)  
Can be conducted at any time of the day and over a large area to assess how fish distribution is affected by cultivation on a larger scale (+)  
Do not face constraints of visual surveys, but echosounders cannot identify species without other verification methods (e.g. capture) (+/−)  
Passive acoustic monitoring devices only detect species that vocalise, e.g. cetaceans (e.g. Ref. 242), but could readily be installed on farms (−/+)| Echosounders should be combined with hand-lining/netting to verify species present (e.g. Ref. 241). | Benthic epifauna: e.g. Ref. 120 (M)  
Finfish: e.g. Refs. 120 (M); 239 (S); 240,241 (F)  
Marine mammals: e.g. Ref. 242 (O) |
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<td>Molecular methods: e.g. environmental DNA (eDNA), antibody techniques</td>
<td>Non-extractive, low-cost, highly replicable and efficient method for multispecies and community analysis, particularly for detecting cryptic, rare or low abundance species that are hard to detect or identify via visual methods. Genetic material can be collected from water, sediment or macroalgal samples easily to detect current or recent presence of species (+)</td>
<td>Need standardised survey and DNA extraction methods, e.g. the time of year for sampling, ensuring suitable replicates are collected to account for dilution in aquaculture, standardisation of filtration pore size for water and sediment samples, and ensuring standardised sequencing methods are used(^{247}) Need improved reference libraries for effective screening of samples, particularly for metabarcoding (the screening of many taxa in one sample simultaneously)</td>
<td>Microorganisms and plankton: e.g. Refs. 55 (W); 54,248,249 (F); 247,250,251 (O); 246 (methods review) Finfish: e.g. Refs. 252 (O); 243 (methods review) Marine mammals: e.g. Ref. 242 (O) Multiple species: e.g. Refs. 253 (M); 244,247,254,255 (W); 256 (O)</td>
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<td>DNA may degrade rapidly under unfavourable environmental conditions (e.g. high temperatures, turbulence, salinity and UV radiation), or depending on the biology of the species(^{243}) Samples may also be contaminated (e.g. by faeces of non-target individuals or via currents from neighbouring areas) (−)</td>
<td>Can distinguish community assemblages separated by only 60 m(^{244}) and estimate biomass and abundance from quantitative models, but may overestimate during spawning periods due to abundant genetic material(^{245}) (+/−) Allows rapid detection of harmful microorganisms and HABs(^{245,246}) but dependent on reference libraries, which are currently lacking (+/−)</td>
<td>Should be deployed alongside other census methods to increase accuracy and confirm species present</td>
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<td>Visual surface searches by experienced observers</td>
<td>Weather, sea state and daylight dependent, which may bias against nocturnal species or shorter day lengths(^{242,145,146}) (−) Time-consuming and restricted to inshore farms unless boats are used to access offshore farms but have the additional cost of boat time and the risk of causing disturbance (−)</td>
<td>Should be conducted before potential disturbance caused by farming to gather baseline data, during any potentially disruptive events e.g. harvesting, and at set time points after disturbance to assess longevity of impact Should be used in combination with more continuous or in-depth methods to gain a more holistic assessment of habitat value</td>
<td>Marine mammals, reptiles and seabirds: e.g. Refs. 140,142,143,146 (S); 145 (F); 257 (S &amp; F)</td>
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<td>Finfish, marine mammals, reptiles and seabirds</td>
<td>Source of low-cost data, where farmers or public contribute sightings/photos of species to central databases or in questionnaires (+) Can yield data on the size range, behaviour, seasonality and frequency occurrence of notable species comparable to other survey methods (+) Enables stakeholder engagement and educates and engages public in the potential benefits of macroalgal cultivation, facilitating social licencing (+) Farmers may visit cultivation sites at different frequencies depending on species cultivated and farm needs. High frequency visits may capture more data but cause additional disturbance to species, whereas more infrequent visits could result in sporadic reporting and could miss key visiting times for certain mobile or short-lived species (+/−) Citizen science surveys only applicable for publicly accessible coastal farms and reference sites (−)</td>
<td>Should be used as a first approach method to establish general species distribution and abundance in the area and then in combination with other more continuous and in-depth methods to gain a more holistic assessment of habitat value Should provide training and simplified methodology guidelines to produce more rigorous and accurate data sets Should increase education and awareness of the importance of healthy marine ecosystems and the ESs they provide to motivate and incentivise surveys</td>
<td>Benthic: e.g. Refs. 258 (F); 259 (O) Finfish: e.g. Ref 235 (F) Marine mammals, reptiles and seabirds: e.g. Refs. 260,261 (O)</td>
</tr>
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and depend on available nutrient concentrations and the scale of cultivation. Differences between model predictions also indicate that further research and ground truthing via in situ data collection are required.

Quantifying plankton assemblages associated with macroalgal cultivation is still in its infancy. Standardised in situ monitoring methods commonly deployed in shellfish and finfish farms could, however, be applied and adapted to better monitor plankton within macroalgal farms (Table 1). This will help to generate more accurate models to quantify habitat value of macroalgal cultivation for plankton assemblages and how it may contribute to other ESs related to HAB mitigation and bioremediation. Better determination of plankton assemblages in macroalgal cultivation sites will also be useful to detect early larval stages of species that may settle on the macroalgae, such as some epibionts (see Section 2.3).

### 2.3 Epibionts

Epibionts, or biofouling species that colonise available surfaces in marine ecosystems, are some of the most studied organisms in aquaculture due to their detrimental impacts on crop production, through reducing crop quality and yield. Macroalgal epibionts such as endophytic or epiphytic algae, bryozoans, amphipods and hydroids may consume or degrade biomass, inhibit photosynthesis and algal growth, encourage grazers, increase disease susceptibility, contaminate commercial products by introducing allergen or toxin risks and damage farm infrastructure, thereby costing the aquaculture industry US$1.5–3 billion yr\(^{-1}\). Farming infrastructure may also facilitate the settlement and spread of invasive non-native epibionts, by offering space for colonisation and reduced biotic resistance.

Nevertheless, for farms that intend to provide non-consumable products, for example, farms that offer the ES of bioremediation (e.g. Ref. 58) or carbon sequestration (e.g. Ref. 90), epibiont colonisation may instead enhance their ES value. Colonising species such as bryozoans, bivalves, sponges, tunicates and other algae may improve water quality and host-plant health through biofiltration and nutrient addition, in turn benefitting shellfish growth, enhancing primary production, providing protection from predation, encouraging settlement of commercially farmed shellfish and mitigating for disease risk. Epibionts also provide food sources for higher trophic level species, increasing the habitat value of a cultivation site and secondary production; however, grazing interactions on epibionts are not currently well understood.

Various studies have found similar or higher levels of epibiont biodiversity associated with cultivated kelps compared to wild populations, which suggests that suspended macroalgal farms could provide novel habitat for epibionts. Epibiont assemblages vary widely between cultivation sites, dependent on latitude, temperature and exposure. Therefore, established, standardised methods are needed to quantify epibionts effectively at different sites. More targeted assessments are also needed to quantify environmentally beneficial epibionts as well as detrimental species to crop production, which have been the focus of studies to date. A better understanding of how epibionts may affect or interact with the environment will also enable a more ecosystem directed view for future development of EAA.

Census techniques for quantifying epibionts are relatively straightforward compared to other farm-associated biodiversity (Table 1), as most species are slow moving or sessile so they can be identified and enumerated directly from macroalgal biomass samples. Previous studies assessing epibiont diversity on macroalgal farms have generally focussed on either the holdfast (e.g. Ref. 105) or the blade (e.g. Refs 100–104) separately however, rather than as one sampling unit. Quantifying the total epibiont assemblage is required if the potential habitat value of macroalgal cultivation is to be fully evaluated.

### 2.4 Benthos

Benthic or seabed communities are comprised of many bioindicator species that signal environmental health and ecosystem functioning, and thus, benthic habitat monitoring is a crucial part of environmental impact assessments supporting aquaculture licence applications. Nevertheless, limited research has been conducted to assess the ecological status below macroalgal cultivation sites compared to the aquaculture of finfish and shellfish. Macroalgal cultivation could affect benthic community structure through shading; changes to hydrodynamic flow; increased sedimentation, organic enrichment, microbial activity and smothering from farm detritus breaking off; and competition with other important neighbouring benthic habitats such as wild kelp forests, seagrass beds or coral reefs (Figure 1, as reviewed in Refs. 5–8,10,12,13). Faeces and pseudofaeces produced by epibionts or mobile organisms associated with macroalgae may also cause benthic impacts that are similar to, although less pronounced than, other aquaculture farm types. Farmers and policy makers can help to mitigate negative impacts on benthos by ensuring macroalgal cultivation sites are deployed at appropriate depths (e.g. Ref. 108). Recent guidelines advising on minimum water depths recommend that farms should be at locations where the water depth is at least twice the depth of the cultivation infrastructure and placed in areas where the minimum water flow rates are >0.05 m s\(^{-1}\). Compared to longline systems that can be deployed offshore, there is often little if any flexibility for cultivation depth for tropical off-bottom farming sites. Clearly, a better understanding of benthic interactions will help inform appropriate siting of farms in suitable environmental conditions to help mitigate for any potential negative effects on the benthos.

Ecosystem models of intensive kelp cultivation scenarios have indicated minimal effects on benthic food webs, or the potential to alter them through the provision of habitat, food and detritus. Effects on benthic species vary between macroalgal cultivation sites globally. In tropical waters, where shallow, bottom-growing
macroalgal cultivation techniques are favoured, significant changes to neighbouring benthic habitats such as corals and seagrass beds and their associated assemblages are often reported (as reviewed in Ref. 10). In temperate waters, where suspended macroalgal cultivation is favoured, benthic impacts tend to be less severe or even negligible (e.g. Refs. 100,101); however, this will depend on water flow rates through the cultivation area and light penetration in the water column. In Sandu Bay, China, however, sedimentary acid volatile sulphide content (linked to lower benthic biodiversity) was greater below kelp cultivation lines than at control sites.118 This emphasises that effects on the benthos need to be evaluated on a site-specific basis, as they will be highly dependent on local environmental conditions and farm type.

Key indicators of benthic habitat health include sediment biogeochemistry (e.g. particle size, nutrient, heavy metal, oxygen-reduction-potential, carbon and organic matter content) and the biodiversity, composition and abundance of benthic infauna and epifauna. Infauna relates to organisms living in the sediment, whereas epifauna relates to organisms living on the seabed. Here, we consider benthic infauna and epifauna as two separate faunal categories, due to the different census techniques required to study them. We focus on both meiofauna (45 μm to 1 mm) and macrofauna (>1 mm) due to their important ecological roles and similar quantification methods.114,115

### 2.4.1 Benthic infauna

Benthic infauna are comprised primarily of detritivores, grazers and filter feeders, such as polychaetes, flatworms, gastropods and bivalves, that all play key roles in recycling nutrients, filtering water and providing prey to epibenthic species.114,116 The diversity and abundance of infaunal assemblages are used as bioindicators of contamination, eutrophication and hypoxia, due to the varying tolerances of species in the community.116,117 It is therefore important to assess how macroalgal farms influence infaunal assemblage structure and function, to monitor the health of the cultivation site and of the wider habitat. Previous studies in offshore seaweed farms in Tanzania have found reduced infaunal biomass118 or that the infaunal assemblages more closely resemble unvegetated areas rather than seagrass beds.119 In contrast, at a Swedish longline farm, increases in infaunal species diversity and abundance have been found, indicating a positive effect of the farm on benthic health.101 The marked differences in farming systems and environmental conditions between these locations (discussed further in Section 3.1) highlights how the effects of macroalgal cultivation on benthic infauna need to be evaluated in more detail. Sampling benthic infauna generally involves taking a sediment grab or core of the seabed and determining its associated fauna and biogeochemical properties100,101,120,121 (Table 1). Benthic survey designs and approaches to the subsequent analysis of infaunal communities can vary greatly, however (Table 1). Standardised monitoring protocols, methods and analyses to quantify impacts from aquaculture on benthic infauna may help to regulate benthic monitoring between aquaculture types and locations in future.

### 2.4.2 Benthic epifauna

Benthic epifauna includes macroinvertebrates (>1 mm), such as echinoderms (e.g. sea stars, urchins and sea cucumbers), crustaceans (e.g. lobsters and crabs) and benthic fish species (e.g. flatfish), many of which are of commercial or ecological importance. Wild kelp populations contribute on average US$48,600 to $141,000 ha−1 yr−1 to capture fisheries across the four major kelp genera globally, with nine of the top 10 valuable species being benthic invertebrates such as lobsters, abalone, urchins and gastropods.122 Macroalgal cultivation may provide similar habitat value to epibenthic species via increased food availability from farm-derived nutrients and detritus (including epibiont cast-off) and the creation of a more heterogeneous habitat (via detritus accumulation or farm infrastructure such as mooring systems).8,17,123–125 At a small temperate kelp farm in Sweden however, no effect on benthic macrofauna was reported,101 whereas in Tanzania, lower abundances of macrofaunal or increases in sea urchin species, that could threaten to graze on the cultivated seaweed, were found.118 Differing effects on epifauna reflect the diverse nature of macroalgal cultivation sites worldwide and highlights the need to increase monitoring across different systems.

Epifaunal assemblages may be more challenging to accurately quantify than infauna, as epifauna tend to be more mobile, patchily distributed and can also be cryptic.126 Monitoring mobile epibenthic macrofauna (>1 mm) may however use similar methods to those used to quantify pelagic fish species (Section 2.5) or marine mammals, seabirds and reptiles (Section 2.6) and these have been summarised and reviewed in Table 1.

### 2.5 Finfish

Finfish species include commercially important species for fisheries or for supporting wider food webs. Macroalgal cultivation sites could provide novel habitat for fish species by offering spawning substrate, shelter and food in the form of farm biomass or epibionts, similar to wild macroalgal populations (reviewed in Refs 10,17,127,128) (Figure 1). Potential benefits to fish species will however depend on farms being sited appropriately, to not replace natural nursery habitats such as seagrass beds, and the habitat complexity created by cultivation sites compared to what was in the area previously.10,127,129 Mariculture infrastructure may also restrict fishing activities in an area, indirectly benefitting fish populations,130 with potential spill-over benefits for fisheries.14 Conversely, however, if macroalgal cultivation sites are poorly managed and regulated, they may act as ‘ecological traps’ whereby fish are attracted to farm infrastructure and become more vulnerable to capture from unregulated fisheries or natural predators, such as seals.10,11,17,131 It is also unclear...
whether macroalgal farms enhance juvenile recruitment or simply aggregate existing adult fish populations. The increased availability of macroalgae and novel epibiont prey on cultivated macroalgae may also alter fish assemblage composition. Illustrating this, increased herbivorous fish biomass was reported in farms in Tanzania compared to neighbouring seagrass beds. Increases in herbivorous fish may be detrimental to farm yields, or conversely beneficial to fisheries in the area; however, it is unclear as to how changes in fish assemblage composition will affect wider ecosystem function. Indeed, fish assemblages in Eucheuma farms in the Philippines were found to be significantly different to those in neighbouring marine protected areas and coral reefs, with more invertivores and fewer large herbivorous fish found in farms and greater biomass and diversity found in neighbouring coral reefs. Conversely, multispecies macroalgal farms in Costa Rica attracted a larger number of fish species compared to control sites. This highlights that the effects of macroalgal cultivation on fish populations can be highly variable between sites and demonstrates the importance of establishing comparative reference sites in survey design (discussed further in Section 3.2).

Finfish species are generally highly mobile and can vary significantly in relation to timing of fish reproductive cycles, which makes accurately surveying their populations challenging. For example, at an Irish seaweed farm, juvenile mackerel and pollack that were found to be abundant in summer months were absent by September, whereas wrasse, which are more associated with the benthos, remained abundant below the site across the whole study period. Inshore fish assemblages are also highly influenced by tides, with greater abundances observed during high tides. Timing of seaweed harvesting is also important for monitoring finfish populations. For example, in wild kelp beds in Norway, juvenile gadoids were 92% less abundant in harvested areas compared to unharvested areas and remained 85% lower in areas one year after harvest. Therefore, standardised medium- to long-term monitoring at multiple spatial scales is required to reliably assess the habitat value of macroalgal cultivation on fish populations and to inform better operational management practices and farm design. Various methods (Table 1) have been used to census fish in macroalgal cultivation sites, many of which are similar to those discussed in epibenthic surveys (Section 5.2). Models of macroalgal cultivation impacts on fish species may aid understanding of ecosystem-wide implications, but should be combined with long-term in situ studies to ground-truth model outputs.

### 2.6 Marine mammals, reptiles and seabirds

Marine mammals, reptiles and seabirds include many species of high conservation importance, so understanding how to manage marine industries to maximise environmental protection and minimise disturbance for these groups is hugely important. These species also play major ecological roles and are of particular value to marine industries such as tourism due to their charismatic value. Here we have grouped these species as they will likely interact with macroalgal cultivation sites in similar ways as they share many life-history traits, and will also require similar surveying techniques to monitor (Table 1).

Potential increases in prey species of fish and macroinvertebrates in macroalgal farms could provide foraging grounds for mammals such as seals and dolphins, reptiles such as turtles, and seabirds, which are frequently observed around finfish and shellfish aquaculture sites (e.g. Refs. 140–146). Farm infrastructure, however, may interfere with the ability for mammals such as dolphins to aggregate fish prey and therefore affect their behaviour and habitat use (as discussed in Ref. 128). Macroalgal cultivation sites may also displace other mammals, reptiles and seabirds due to farm construction and operation activities (e.g. as seen in shellfish aquaculture), which could lead to malnutrition if animals are displaced from their foraging grounds. Minimal risks to cultivated macroalgae are perceived from vertebrate predators (unlike other aquaculture species), and they may instead help to maintain trophic balance and control grazing species as seen in wild populations. Herbivorous species such as green turtles (Chelonia mydas, Linnaeus, 1758), however, have been found to consume some cultivated macroalgae, which may attract them to cultivation sites, causing conflicts between turtles and farmers or increasing entanglement risk. Other species are also susceptible to entanglement risk with farming infrastructure, as seen with stationary fishing gear or some mussel lines. Lethal entanglement of critically endangered dugongs (Dugong dugon, Lacépède, 1799) has been reported in cultivation sites in the Philippines. Entanglement risk is generally well understood however, and can be mitigated by increasing line thickness and tautness and avoiding placement in areas of known importance, such as migratory corridors. Nevertheless, there are still considerable uncertainties about how large-scale farms that occupy large surface areas of coastal seas or entire bays influence marine mammals, reptiles and seabirds.

Census of marine mammals, reptiles and seabirds is challenging due to their generally low population densities and highly mobile existence. Furthermore, surveys need to be conducted over long timescales to fully assess impacts of cultivation sites on their populations, because many have long lifespans and slow population growth. Monitoring of these species therefore requires immense survey effort or specialist behavioural knowledge, and is usually conducted from land, boats or air, often relying on species breaching or being at the surface of the water to be visible (Table 1). Currently, there are very limited studies on the interactions of marine mammals, reptiles or seabirds with macroalgal farms and further research to address this knowledge gap is essential to enable better management and enhance potential habitat benefits of cultivation sites. Recent reviews have been published regarding census around marine renewable energy infrastructure (e.g. Ref. 160) and other aquaculture types, which can inform monitoring in macroalgal cultivation sites (Table 1).
3 | GENERAL RECOMMENDATIONS ON STUDY DESIGN FOR MONITORING HABITAT PROVISIONING IN MACROALGAL CULTIVATION SITES

This review illustrates that it is not only the monitoring approach used that is important for quantifying habitat provisioning in macroalgal cultivation sites but also how and when these surveys are carried out. Standardised approaches in study design and implementation will ensure monitoring is more directly comparable across farm sites and scales, including IMTA and offshore systems. The effectiveness of different survey methods will differ between farm types, however, which we discuss further below (Section 3.1).

Here, we provide the first steps in standardising monitoring protocols for assessing habitat provisioning by macroalgal cultivation, with regard to accounting for differences in farm types, establishing reference sites, timing surveys appropriately and defining the necessary species metrics to be taken for relevant habitat value analysis. We also discuss how the collection of appropriate field data can be used in models to answer some of the broader, ecosystem-wide necessary species metrics to be taken for relevant habitat value analysis. The effectiveness of different survey methods will differ between farm types, however, which we discuss further below (Section 3.1).

Here, we provide the first steps in standardising monitoring protocols for assessing habitat provisioning by macroalgal cultivation, with regard to accounting for differences in farm types, establishing reference sites, timing surveys appropriately and defining the necessary species metrics to be taken for relevant habitat value analysis. We also discuss how the collection of appropriate field data can be used in models to answer some of the broader, ecosystem-wide effects of the habitat value of macroalgal cultivation that extend beyond the footprint of the farms, and importantly how these data can be shared in open-access repositories to advance the sustainable design of macroalgal cultivation sites in EAA.

3.1 | Accounting for differences in macroalgal cultivation farm types

Globally, there is a wide diversity of macroalgal farm types and species cultivated, from offshore temperate kelp farms to off-bottom tropical carrageenophyte cultivation (Figure 1). This diversity makes creating standardised monitoring techniques to quantify habitat provisioning challenging, as their effectiveness will differ widely between cultivated species, locations and farm types. From the monitoring techniques outlined in Table 1, many of these are applicable to all macroalgal cultivation sites globally. For example, diver-conducted visual surveys of fish and pelagic species have been used successfully in both Eucheuma and Kappaphycus farms in the Philippines and Codium, Gracilaria, Sargassum and Ulva farms in Costa Rica. This survey method is straightforward and flexible due to divers or snorkelers being able to adapt their positions around farming infrastructure. Between farm types, where infrastructure differs greatly however, some monitoring techniques are not feasible to deploy universally. For instance, small beam trawls may be suitable for monitoring benthic species around kelp longline systems (as conducted in a Canadian mussel farm); however, they are not suitable in most tropical macroalgal farms due to shallow depth limitations, high density of cultivation lines or use of mesh nets to seed (e.g. in Pyropia or Ulva farms). To survey benthic species in shallow tropical farms, more targeted methods could be deployed, such as benthic drop cameras or traps (Table 1), which can also be used successfully in temperate systems. Remote camera surveys would also cause less disturbance to both biodiversity and the cultivated species. To enable more effective comparison of habitat value between macroalgal cultivation sites globally, monitoring methods that are flexible in terms of their deployment should be favoured over those that will only work in certain cultivation scenarios.

Working collaboratively with farmers or other stakeholders, such as local fisheries, will enable suitable survey methods for the region to be developed. For example, in Tanzanian off-bottom Eucheuma and Kappaphycus farms, where trawling or netting is not possible, researchers used traditional ‘madema’ basket traps to survey fish populations, and were instructed on best deployment techniques by local fishermen. Using local methods and knowledge-enabled successful catches of fish populations in relation to macroalgal cultivation sites and also to assess how the presence of macroalgal cultivation sites may affect the economic value of other marine industries in the area. Engaging with farmers and other local industries may also help to improve awareness of the potential ecological and economic benefits of habitat provisioning by macroalgal cultivation and therefore increase interest in contribution to farmer or citizen science observations or the uptake of habitat monitoring into farm management protocols (Section 3.7).

3.2 | Surveying appropriate reference sites and environmental variables

Ideally, to fully assess the environmental effects of an aquaculture system, surveys should be conducted before farms are established in any given area, and then compared to results seen during and after implementation, as well as at control sites, thereby adopting a before-after-control-impact (BACI) design. Beyond BACI studies may often include multiple, additional control sites away from the farm, which experience similar background environmental conditions to the farm site (e.g. depth, sediment, hydrology) but are at an appropriate distance away so as to not be affected by the presence of aquaculture species (e.g. Refs. 100,101). Where macroalgal cultivation sites have already been implemented before baseline conditions were established, habitat value has often been compared to other reference habitats, such as seagrass beds (e.g. Ref. 129) or wild macroalgae populations (e.g. Ref. 105). To understand any added habitat value created by macroalgal cultivation sites to an area, farms should also be compared to areas with similar environmental conditions where there is no structural habitat, as this is where farms are often implemented. Factoring in the monitoring of other variables such as macroalgal species and biomass, depth, light, temperature, sediment and water biogeochemistry (e.g. dissolved inorganic carbon, sediment size and oxygen-reduction-potential), nutrient availability and hydrodynamic activity, will also be required to accurately compare the habitat value of different farms and better understand the health of these systems. To assess the effect of habitat provisioning beyond the direct footprint of a cultivation site, reference sites can be set at incremental distances away from the site to determine a sphere of influence or radius...
of attraction for species (e.g. Ref. 124). In many aquaculture sites, wider effects can be relatively small, e.g. limited to <50 m for epibenthic macrofauna in Canadian blue mussel farms.124 For different taxonomic groups however, it is likely that the influence of cultivation sites will extend further outside of the farm’s footprint, such as for larger megafauna that may be deterred from foraging grounds, as observed with dolphins and shellfish aquaculture in New Zealand.147,148

### 3.3 | Timing of surveys

Previous studies have often only sampled at harvesting time points (e.g. Ref. 263), when successional communities may not be fully established. This is representative for the farming industry, which normally completely removes algal biomass at harvest; however, time-series data that extend beyond typical harvesting seasons could inform better harvesting practices to maximise the habitat value of macroalgae farms and inform EAA. For example, trials are being conducted to assess how partial harvesting techniques (whereby some of the holdfast and blade are left in situ) may influence epibiont communities and extend the biodiversity value and crop yield of the farms.80,87 Surveying beyond the cultivation season, when macroalgal biomass is removed, will also help to determine to what extent the habitat value of the site has been removed in the absence of the algae and indeed whether it might be maintained, at least in part, by the presence of farm infrastructure in the area (if this remains in place).79,264 Sampling should therefore be conducted at multiple or continuous set time points before, during and beyond multiple harvesting cycles, to help avoid temporal bias, allow comparability and more completely estimate the habitat value of cultivation sites, as well as determine whether or not they provide habitat only during cultivation seasons.

### 3.4 | Species metrics to be taken and statistical analyses of habitat value

Quantifying the habitat value of macroalgal cultivation sites does not only rely on determining the species present in the site and their abundances but also on understanding their usage of and behavioural interactions with the site at various life stages in the long term, as well as monitoring their physiological condition and fitness (e.g. juvenile recruitment). Juvenile recruitment success underpins population fitness and biodiversity, so it should be monitored within cultivation sites and surrounding areas to address whether macroalgal farms enhance wild populations through juvenile recruitment or simply aggregate individuals from surrounding areas. Quantifying the size and nominal age of individual organisms is also needed to understand juvenile recruitment.8,124 Biomass measurements are also important to determine nutrient and energy flows in ecosystem-wide and food web models220 (see Section 3.5), but can be estimated for wild fish using published length–weight conversions (e.g. ecoCEN225). Many of the methods outlined in Table 1 are capable of determining size and age classes of individuals, through the direct measurements of captured, from photographed organisms using a scale, or through visual estimates from experienced divers or observers (e.g. Ref. 200). Visual methods are also often necessary to determine the behavioural activity of species at macroalgal cultivation sites, for example, feeding, breeding and sheltering or avoidance of the site. Tagging or biologging species also allows the behaviour of individuals to be monitored and site fidelity to be established.238 Feeding behaviour can also be determined through gut content or isotopic analysis (e.g. Ref. 266), which can establish food web effects of the farm. Better knowledge of species’ activity and feeding behaviours will help determine what attracts them to farming infrastructures, and the significance of the farm habitat. This will furthermore help to improve the understanding of how farming practices can be better designed to maximise the habitat value of macroalgal cultivation sites and mitigate disturbance on key life stages of inhabiting species, through EAA.

The use of diverse biotic indices and statistical approaches can also provide various insights into overall community and ecosystem health, determining the habitability of an area for different species. For example, to quantify infaunal biodiversity, a large variety of statistical approaches183,267,268 and biotic indices are used (summarised in Refs. 117,269). Indices lend themselves to standardisation and they can be fine-tuned to detect certain types of pressure, for example, the Infaunal Trophic Index (ITI), which takes into account species sensitivity to organic enrichment could be used to quantify the impact of organic exudates and cast-off from macroalgal farms. The Infaunal Quality Index (IQI) is also used to assess sediment quality and would be useful for detecting disturbance below macroalgal cultivation sites.267 When multiple indices are employed, they generate a wider picture of the impacts of aquaculture.117,271–273 The choice of data analysis tools is therefore important and should be considered carefully when designing habitat value surveys to ensure they fulfil assessment objectives and are comparable to other sites.

For comparability of habitat value between cultivation sites and aquaculture species, a standardised set of variables, biotic indices and statistical approaches should be produced, which would enable better quantification of the habitat value of macroalgal cultivation.117 Such assessment criteria exist for reviewing the impacts of human activities on the marine environment, such as the Marine Evidence Based Sensitivity Assessment (MarESA).274–276 MarESA can be applied to monitoring different forms of aquaculture and their impacts in terms of magnitude, extent, duration and frequency of the effect, so that pressures from different activities can be compared on an equal footing.

### 3.5 | Modelling the wider ecosystem effects of habitat provisioning for an ecosystem approach to aquaculture (EAA)

Despite the increasing number of survey methods available for quantifying habitat provisioning in macroalgal cultivation sites, the resources available to conduct such field surveys are limited, particularly at small-scale farms and they tend to focus within a farm’s footprint.
Models may be used instead to predict ecosystem-wide effects based on established relationships with primary productivity, nutrient and energy flows and readily available environmental and species data.

At macroalgal cultivation sites, models have already been run for determining effects on plankton assemblages at different farm scales (e.g. Refs. 65,67,71,73,74) and ecosystem-wide effects on food web dynamics (e.g. Ref. 120). Models of carrying capacity in aquaculture systems assess the maximum production potential of a cultivated species that can be supported in an area based on environmental conditions, optimal stocking density, cultivation approaches and environmental impact.72,277 Carrying capacity models can be used in the development of EAA to assess ecosystem impacts beyond the direct footprint of the cultivation site and ensure sustainability.277,278 In Sanggou Bay, China, carrying capacity models have been used to assess production limits of cultivated kelp and oysters based on species growth dynamics and environmental data279; however, these did not focus on the ecological carrying capacity of the site, rather on maximising production. Ecological carrying capacity in macroalgal cultivation sites should be investigated further to balance production with ecosystem management goals, as has been outlined for shellfish and finfish cultivation previously.73,277,278

Although models rely on initial species input data from field surveys to be calibrated, ground truthed and verified, data from other prepublished studies and reports can also be used.120 As ecosystems are complex, models can tend to oversimplify aquaculture–environmental relationships71; however, as our understanding of these systems improves, the usefulness of habitat provisioning models will also increase. Models can also be used to assess cumulative ecosystem impacts of IMTA systems or multipurpose platforms such as integrated aquaculture and marine renewable energy sites to inform marine spatial planning and policy related to EAA.280

3.6 | Data distribution and access

In order to inform decisions on optimising the habitat value of macroalgal cultivation sites in EAA, high quality comparable data from multiple sites will need to be used. To facilitate this, global standardised data sets should be generated with available data on habitat provisioning in macroalgal farms or other aquaculture types. Conceptual frameworks such as the Essential Biodiversity Variables (EBVs)281 could aid in creating interoperable data sets based on data collected using common methodologies. These frameworks could then be made available in open-access repositories to facilitate habitat value or biodiversity assessments.282

3.7 | Integration of monitoring techniques into farm management protocols and policy

Currently, policy relating to macroalgal cultivation at either national or international level is not well established, and farm management protocols are often focused on reducing waste, pollution, disease outbreaks and damaging epibionts, rather than maximising the ecological value of the site. Standardised quantification of habitat provisioning of macroalgal cultivation sites would be greatly facilitated through the creation of clear monitoring criteria and guidance from regulatory and accreditation bodies through farm management protocols or policy.5,13,107 Monitoring techniques should adhere to licencing and certification standards, whilst also benefitting farmers to incentivise their usage, for example, via optimising harvest schedules and increasing product yield and grade or facilitating regulation and licencing of farms. Several sustainability and organic certification standards for macroalgal cultivation production (outlined in Ref. 9) discuss the need for farmers to assess the positive and negative environmental impacts of their farms and establish sustainable management plans to enable their products to be accredited; however, very little direct guidance on evidence-based monitoring is given. For example, the Aquaculture Stewardship Council (ASC)-Marine Stewardship Council (MSC) sustainable seaweed standard for both wild and farmed seaweeds sets a number of requirements for farmers to demonstrate that they are actively reducing any potential negative environmental impacts of their farms, including on native species and habitats.283 Elements of the ASC-MSC standard include habitat, ecosystem structure and function, species status, species management, waste management and pollution control, energy efficiency, disease and pest management practices and introduced species management. The ASC-MSC standard does not, however, detail any specific monitoring techniques required to provide evidence for this. If certification standards could encourage this form of standardised data collection as a requirement for certification, it would greatly incentivise farmers to integrate habitat provisioning monitoring techniques into their current farm management protocols. Standardising methods for quantifying habitat provisioning and the associated ecological (and economic) value is undoubtedly more challenging than for data collection related to assessing and managing impacts around waste management and pollution control, energy efficiency, disease and pest management practices. However, encouraging monitoring of habitat provisioning is essential for realising an EAA and assuring the sustainability of the industry.72

Marine licencing bodies could also set environmental and habitat monitoring as a legal requirement to grant farming permissions, particularly in newly emerging regions of macroalgal cultivation, such as Europe. The EU strategic guidelines for a more sustainable and competitive EU aquaculture in 2021–2030 highlights the limited data reported on environmental indicators related to aquaculture and the need to oblige farmers to monitor and report environmental data to licencing systems and for regulating bodies to enforce sanctions for non-compliance.72 The environmental data currently reported relates mostly to water quality and pollution levels72; however, reporting could be expanded to include biodiversity or habitat monitoring.13 To engage other stakeholders and facilitate social licencing, monitoring techniques could also be targeted at verifying potential economic benefits to other marine industries, including fisheries,
by identification of commercially important species such as edible crabs, fish and lobsters.72

4 | CONCLUSIONS

Macroalgae cultivation may provide several key ESs, which could increase cultivation value beyond that of biomass production alone. Macroalgae cultivation sites could provide important habitat for a diverse number of species of ecological, conservation and/or commercial importance. However, the habitat provisioning of macroalgal farms largely remains unquantified and consequently, placing economic values on this environmental benefit remains uncertain. If the habitat value of macroalgal cultivation sites can be effectively quantified, this would incentivise farmers to design cultivation sites or harvesting schedules to maximise habitat value and contribute towards sustainable EAA. With growing exploitation of the marine environment and increasing fragmentation and degradation of marine habitats, the strategic implementation of restorative EAA may provide important wildlife corridors to reconnect habitats and support complementary communities of fish and fishing grounds, which may otherwise take decades to recover unaided.284 Better understanding of the species that occupy macroalgal cultivation sites is therefore important and requires comprehensive and robust census techniques and methods specifically designed for use in macroalgal farms, due to the unique challenges these habitats pose for monitoring. With the increasing proportion of large-scale offshore or IMTA sites, census techniques should be designed to survey in a variety of environmental conditions and at differing cultivation scales globally. Standardising methods for quantifying habitat provisioning and its ecological (and economic) value is challenging due to wide ranging taxonomic and functional groups that can inhabit seaweed farms; however, this work is essential for realising EAA and assuring the sustainability of the industry. A future challenge for quantifying the value of habitat provisioning will be to harness the data generated from employing standardised methods and move beyond summative assessments or indices of biodiversity to more ecosystem-based assessments, which take into account species–species and species–environment interactions and synergies.

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AUTHOR CONTRIBUTIONS

Sophie Corrigan: Conceptualization; Investigation; Writing – original draft. A. Ross Brown: Conceptualization; Funding acquisition; Supervision; Writing – review & editing. Ian G. C. Ashton: Funding acquisition; Supervision; Writing – review & editing. Dan A. Smale: Funding acquisition; Supervision; Writing – review & editing. Charles R. Tyler: Conceptualization; Funding acquisition; Supervision; Writing – original draft; Writing – review & editing.

DATA AVAILABILITY STATEMENT

No data were generated for this review.

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