

1 **Opportunities for seagrass research derived from remote sensing: a review of**
2 **current methods**

3 Bijeesh Kozhikkodan Veetil^{1,2}, Raymond D Ward^{3,4}, Mariana Do Amaral Camara Lima³,
4 Milica Stankovic⁵, Pham Ngoc Hoai⁶, Ngo Xuan Quang^{7,8,*}

5
6 ¹ Institute of Fundamental and Applied Sciences,
7 Duy Tan University, Ho Chi Minh City, 700000, Vietnam
8 Email: bijeeshkozhikkodanveetil@duytan.edu.vn

9
10 ² Faculty of Information Technology,
11 Duy Tan University, Da Nang, 550000, Vietnam

12
13 ³ Centre for Aquatic Environments,
14 University of Brighton, Moulsecoomb, Brighton, BN2 4GJ, United Kingdom
15 Email: R.D.Ward@brighton.ac.uk

16
17 ⁴ Institute of Agriculture and Environmental Sciences,
18 Estonian University of Life Sciences, Kreutzwaldi 5, EE-51014, Tartu, Estonia

19
20 ⁵ Excellence Centre for Biodiversity of Peninsular Thailand,
21 Faculty of Science,
22 Prince of Songkla University, Hat Yai, Songkhla, 90110, Thailand

23
24 ⁶ Faculty of Natural Sciences,
25 Thu Dau Mot University, Thu Dau Mot City, Binh Duong, Vietnam
26 Email: hoaipn@tdmu.edu.vn

27
28 ⁷ Environmental Quality, Atmospheric Science and Climate Change Research Group,
29 Ton Duc Thang University, Ho Chi Minh City, Vietnam

30
31 ⁸ Faculty of Environment and Labour Safety,
32 Ton Duc Thang University, Ho Chi Minh City, Vietnam

33
34 *Correspondence: ngoxuanquang@tdtu.edu.vn

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37 **Abstract:** Seagrass communities provide critical ecosystem and provisioning services for both
38 human populations and a wide range of associated species globally. However, it has been
39 reported that seagrass area is decreasing at a rapid rate in many parts of the world, mostly due to
40 anthropogenic activities including global change (pollution and climate change). The aim of this
41 review article is to highlight the range of current tools for studying seagrasses as well as identify
42 the benefits and limitations of a range of remote sensing and traditional methodologies. This
43 paper provides a discussion of the ecological importance of seagrass meadows, and recent trends
44 and developments in seagrass research methods are discussed including the use of satellite
45 images and aerial photographs for seagrass monitoring and various image processing steps that
46 are frequently utilised for seagrass mapping. The extensive use of various optical, Radar and
47 LiDAR data for seagrass research in recent years has also been described in detail. The review
48 concludes that the recent explosion of new methods and tools available from a wide range of
49 platforms combined with the recent recognition of the importance of seagrasses provides the
50 research community with an excellent opportunity to undertake a range of timely research. This
51 research should include mapping the extent and distribution of seagrasses, identifying the drivers
52 of change and factors that confer resilience, as well as quantification of the ecosystem services
53 provided. Whilst remotely sensed data provides an important new tool it should be used in
54 conjunction with traditional methods for validation and with a knowledge of the limitations of
55 results and careful interpretation.

56

57 **Keywords:** Submerged marine vegetation, Coastal ecosystems, Marine environment, Coastal
58 management.

59

60 **1. Introduction: Seagrass communities and their ecological importance**

61 Seagrass meadows are regarded as some of the most productive ecosystems, together
62 with salt marshes, mangroves and coral reefs (Costanza et al. 1998; Ward et al. 2016a; Veettil et
63 al. 2018a,b). Seagrasses occupy lower elevation coastal areas than salt marshes and mangroves
64 (Short et al. 2007; Fortes 2012; Lima et al. 2020), and as a result are more frequently inundated,
65 with seagrasses typically located in lower intertidal or subtidal zones.

66 Seagrasses have a wide global distribution, covering temperate and tropical coastlines
67 across 6 different bioregions, namely: 1. Temperate North Atlantic (from North Carolina, USA
68 to Portugal); 2. Tropical Atlantic (both tropical coasts of Atlantic, Caribbean Sea, Gulf of Mexico,
69 Bermuda and the Bahamas); 3. Mediterranean (Mediterranean Sea, the Black, Caspian and Aral
70 Seas and northwest Africa); 4. Temperate North Pacific (From Korean Coast to Baja, Mexico);
71 5. Tropical Indo-Pacific (tropical Australia to the eastern Pacific, East Africa, and South Asia); 6.
72 Temperate Southern Oceans (New Zealand, temperate Australia, South America and South
73 Africa) (Short et al. 2007) (**Figure 1**). Seagrass species diversity varies with region, with the
74 highest diversity found in South East Asia (Green and Short 2003). Two environmental variables
75 that strongly influence the distribution of seagrasses are sea surface temperature (SST) and
76 salinity (Chefaoui et al. 2016). Other factors include turbidity, water currents, solar radiation,
77 nutrients, oxygen and sulphides (McMahon et al. 2014; Glasby et al. 2015). The distribution of
78 seagrasses in different climate conditions can be species dependent (Short et al. 2007). For
79 example, key seagrass genera along the tropical coastal areas are: *Cymodocea*, *Enhalus*,
80 *Halodule*, *Halophila*, *Syringodium* and *Thalassia*; whereas *Amphibolis*, *Phyllospadix*, *Posidonia*
81 and *Zostera* dominate in temperate regions; and *Thalassodendron* and *Ruppia* have a global
82 distribution (Short et al. 2007). Due to the influence of various environmental factors on seagrass

83 distribution, these species can be considered as excellent bio-indicators of climate change and
84 ecosystem health (Foden et al. 2013; Fourqurean et al. 2012; Marba et al. 2013).

85 Seagrasses play an important role as primary producers, as well as providing a habitat
86 and breeding ground for many marine animals including shrimp, sea urchins and clams, and
87 endangered species, such as turtles and marine mammals (e.g. dugong and manatee), and
88 migratory birds (e.g. *Egretta* spp.) (Bujang et al. 2006; Short et al. 2007; Fortes 2012).
89 Seagrasses can also act as a buffer between land and marine environments, filtering nutrients and
90 contaminants from the water column, and reducing turbidity by slowing currents and trapping
91 suspended sediment particles (Fortes 2012; Potouroglou et al. 2017). Seagrasses also play an
92 important role in climate change mitigation through rapid rates of carbon sequestration and high
93 carbon storage capacity, which can be locked away for millennia (McLeod et al. 2011; Duarte et
94 al. 2013; Duarte and Krause-Jensen 2017).

95 In addition to their role as carbon sinks, seagrass meadows have historically provided
96 numerous ecosystem services, directly or indirectly, dating back to the 16th century (Campagne
97 et al. 2015; Cullen-Unsworth et al. 2014; Nordlund et al. 2016, 2017). A few examples of these
98 come from centuries old records of seagrass litter being used as bedding, straw substitutes for
99 thatching stoned roofs in Scotland, and even in agriculture (Urquhart 1824; Willis 1983;
100 Terrados and Bodrum 2004; Nordlund et al. 2016). Furthermore, small-scale fisheries are largely
101 dependent on seagrass communities and their role as nursery areas for various economically
102 valuable fish species and marine invertebrates (Torre-Castro et al. 2014; Unsworth and Unsworth
103 2016; Nordlund et al. 2017; Vonk et al. 2008; Jones et al. 2018).

104 Despite the high economic value provided by ecosystem services, seagrass area is in
105 global decline due to a range of factors including alterations in coastal habitat (Micheli et al.

106 2008), eutrophication (Burkholder et al. 2007), invasive algal or plant species (e.g. *Caulerpa*
107 *taxifolia*) (Short et al. 2007), invertebrate grazing (Statton et al. 2015), sea level rise (Saunders et
108 al. 2013; Garner et al. 2015), climate extremes (Arias-Ortiz et al. 2018) and climate change
109 (Duarte et al. 2018; Lima et al. 2020) and regional climate impacts such as high energy storms
110 (Orth et al. 2006a; Duarte et al. 2008; Waycott et al. 2009). Seagrass decline is one of the factors
111 accelerating the broader degradation of marine habitats around the world (Waycott et al. 2009).
112 Due to the high importance and value of seagrass ecosystem services to global biodiversity,
113 human well-being and climate change mitigation, it is crucial to understand and acknowledge
114 research methodologies for evaluating the location, extent and ecosystem health and benefit of
115 seagrass systems. To date, seagrass monitoring methods have primarily used in-situ approaches
116 including SCUBA/snorkeling surveys (Gotceitas et al. 1997), ground-based sampling (Moore et
117 al. 2000), and hovercraft-based mapping (McKenzie 2003). More recently, active and passive
118 remote sensing approaches have been introduced to estimate the cover and quality of seagrass
119 habitats (Duffy et al. 2018). Other methods, such as active acoustic remote sensing using side
120 scan sonar, have also been deployed to quantify seagrass meadow cover (Barrell et al. 2015;
121 Hossain et al. 2015b), whilst passive spectral sensors on-board platforms such as satellites or
122 light aircraft have proven useful to quantify seagrass meadow dynamics (e.g. Baumstark et al.
123 2016; Cunha et al. 2005). However, remote sensing techniques still have limitations to be
124 overcome, especially regarding spatial resolution, which restrict the focus of studies to
125 identification and mapping of seagrass areal extent. Even using fine spatial resolution satellite
126 data, individual seagrass plants or shoots cannot be detected (Stekoll et al. 2006; Valle et al.
127 2015; Duffy et al. 2018). For this reason, the development of new and scale-appropriate methods

128 for quantifying and monitoring changes in seagrass ecosystems remain important, to improve the
129 way that drivers of change are understood, and allow for improved management.

130 The aim of this review article is to provide an overview of seagrass research methods in
131 order to highlight limitations and benefits to using various techniques derived from a range of
132 remote sensing platforms (spaceborne/airborne/UAV/AUV/boat), including passive and active
133 methods such as hyperspectral, multispectral, stereoscopic aerial imagery, LiDAR, RADAR and
134 side scan, and the added benefits of combining these with traditional research methods.

135

136 **2. The role of remote sensing in seagrass research**

137 For a global level assessment of various terrestrial and marine ecosystems, field surveys
138 are too time consuming and expensive. Remote sensing, particularly using spaceborne datasets,
139 can provide relevant and long-term data for analysing ecosystem changes ([Murray et al. 2018](#)).
140 Spaceborne and airborne remote sensing has been widely used for monitoring and mapping
141 seagrass ecosystems throughout the world ([Chauvaud et al. 1998](#); [Dekker et al. 2007](#)). Recently,
142 methods for the acquisition and interpretation of optical/acoustic data for the mapping of
143 seagrass habitats have advanced rapidly ([Ferwerda et al. 2007](#); [Hossain et al. 2015b](#)). Remote
144 sensing applications on seagrass ecosystems can be primary (detection of seagrasses, spatial
145 coverage, species-level discrimination, biomass detection, growth patterns and degradation) or
146 secondary (environmental variables influencing seagrasses such as SST, salinity, sea-level rise,
147 pollution, detection of epiphytes, etc.) ([Chauvaud et al. 1998](#); [Dekker et al. 2007](#); [Ferwerda et al.](#)
148 [2007](#); [Hossain et al. 2015b, 2019](#)).

149 Compared with terrestrial plant ecosystems, seagrass ecosystems are more dynamic and
150 change significantly over space and time ([Frederiksen et al. 2004](#)) and the principle difficulty in

151 seagrass remote sensing (particularly when using passive remote sensing systems) arises from
152 the fact that these are often submerged (Duffy et al. 2018). Despite these difficulties remote
153 sensing surveys of seagrass ecosystems can be undertaken using terrestrial/underwater
154 photography and videography, airborne data (including unmanned aerial vehicles - UAVs), and
155 satellite imagery (Hossain et al. 2015b).

156

157 **2.1 Principles of seagrass remote sensing**

158 Many direct remote sensing methods are based on spectral reflectance measures of
159 chlorophyll and other constituents in leaves (Qiu et al. 2019). Leaf reflectance characteristics are
160 influenced by surface features, structure and biochemical components of the leaf (Thorhaug et al.
161 2007). The spectral reflectance of seagrasses and attenuation of the useful portion in the
162 electromagnetic spectrum (mainly visible [400-700 nm] and infrared radiation [1000-2000 nm])
163 by its surrounding aquatic environment are key factors influencing the quality of seagrass remote
164 sensing (Thorhaug et al. 2006). Electromagnetic radiation (EMR) from the sun (for passive
165 remote sensing) or the sensor (for active remote sensing) undergoes atmospheric scattering and
166 underwater attenuation twice for each medium. Large differences in reflectance in visible and
167 infrared wavelengths are used for discriminating terrestrial plants using optical remote sensing
168 (Borregaard et al. 2000). However, in the case of submerged seagrass communities, the visible
169 wavelength penetrates the water column whereas wavelengths beyond 680 nm undergo
170 significant attenuation (Kirk 1994; Kirkman 1996) and hence the most suitable method while
171 using optical data is to utilize the differences in spectral reflectance within visible wavelengths
172 (Dekker et al. 2007). Both atmospheric correction and estimating the water attenuation

173 coefficient are necessary for mapping seagrass communities using optical remote sensing data
174 ([Giardino et al. 2019](#)).

175 In coastal waters, spectral scattering and absorption by phytoplankton, suspended
176 sediments and dissolved organic substances further restricts the application of remote sensing of
177 seagrasses ([Dekker et al. 1992](#); [Giardino et al. 2019](#)). Underwater absorption of electromagnetic
178 radiation is principally caused by phytoplankton, organic and inorganic particulates, dissolved
179 organic materials and water molecules whereas scattering is mainly caused by suspended
180 (organic/inorganic) sediments ([Hossain et al. 2015b](#)). Absorption and scattering increase with
181 depth through the water column, causing an exponential reduction in light intensity, which
182 means that the possibility of spectral discrimination of seagrass communities using optical
183 remote sensing data rapidly decreases with depth ([Zimmerman and Dekker 2007](#)).

184

185 **2.2 Types of remote sensing data for seagrass research**

186 A wide range of remotely sensed datasets, including aerial, terrestrial and underwater
187 photography, and satellite imagery have been used for seagrass research in recent decades (e.g.
188 [Mumby et al. 1997](#); [Dekker et al. 2007](#); [Hossain et al. 2015b, 2015c](#); [Hossain and Hashim 2019](#)).

189 Both active and passive sensors have been employed for data collection in recent years and used
190 for seagrass research ([Ferwerda et al. 2007](#); [Hossain et al. 2015b](#); [Duffy et al. 2018](#)). Various
191 factors dependent on the objective of the study need to be considered when selecting remotely
192 sensed data for seagrass research, including: spatial resolution, spectral resolution (e.g.
193 multispectral and hyperspectral), radiometric resolution, temporal coverage, remote sensing
194 system (active or passive), platform (e.g. terrestrial, underwater, airborne, spaceborne) and
195 ranging techniques (e.g. Radar, LiDAR).

196 In this paper, we have classified the data used for seagrass research as airborne and
197 spaceborne remote sensing. However, active remote sensing systems (Radar and LiDAR) are
198 discussed separately because distinct acquisition and processing techniques are applied while
199 using these datasets. Furthermore, a separate section is provided to discuss new trends in using
200 UAVs for seagrass research.

201

202 **2.2.1 Seagrass remote sensing using terrestrial and underwater photography/videography**

203 Terrestrial photographs have been traditionally used for documenting coastal areas
204 ([Robbins and Bell 1994](#)). However, due to a number of limitations, very few studies exist on the
205 use of this method for mapping or monitoring seagrass habitats (e.g. [Andrade and Ferreira 2011](#);
206 [Gonzalez 2015](#)) compared to underwater photography/videography (e.g. [Burdick and Kendrick](#)
207 [2001](#); [McDonald et al. 2006](#)). Terrestrial oblique large-scale photography can be used for cost-
208 effective and repeated coverage over short time intervals, even though ground control points
209 (GCPs) using a GPS tracker are required for image rectification and to create orthogonal views
210 for mapping seagrass meadows by applying a suitable image classification algorithm ([Andrade](#)
211 [and Ferreira 2011](#)). Recently, [Alvsvåg \(2017\)](#) used photographs from a DSLR camera mounted
212 on an Autonomous Surface Vehicle (ASV) to map seagrass habitats in Hopavågen (Norway).

213 Underwater photography ([Figure 2](#)) and videography are widely used for regional-scale
214 seagrass habitat studies, including the interrelationship among organisms ([Norris et al. 1997](#);
215 [Burdick and Kendrick 2001](#); [McDonald et al. 2006](#)). Images and/or video can be taken by
216 SCUBA divers or using remotely operated or autonomous underwater vehicles (AUVs)
217 ([Armstrong et al. 2006](#)), towed or drop-down video ([Andrade and Ferreira 2011](#)). Underwater
218 photography can be used for measuring structural characteristics, such as the number of leaves,

219 leaf length, and shoot density (Borg et al. 2006). Underwater videography can also be used for
220 detecting changes in seagrass cover (e.g. McDonald et al. 2006), characterization of seagrass
221 habitat (e.g. Haag et al. 2008) and species identification in extremely shallow or clear water
222 (Norris et al. 1997). AUVs are very time-effective, since they can be used to measure canopy
223 structure and estimate above-ground biomass using captured stereo imagery (Roelfsema et al.
224 2015). Furthermore, AUV data can be used for calibrating and validating satellite data
225 (Roelfsema et al. 2015), as AUV data collection can have spatial and temporal consistency,
226 repeatability, and be used in deeper waters. AUVs can also capture stereo imagery to measure
227 canopy structure and to estimate above-ground biomass and can be compared with labour
228 intensive in situ data collection (Roelfsema et al. 2015). Light-weight AUVs are used effectively
229 in seagrass research (e.g. Vasilijevic et al. 2014) and the integration of AUV data with high
230 resolution satellite data (e.g. WorldView-2, IKONOS) can offer high quality, multi-temporal
231 mapping of seagrass at a species level as well as biomass estimation (Roelfsema et al. 2014).
232 Tecchiato et al. (2015) successfully utilised underwater photography integrated with sediment
233 data and geomorphological information to understand the influence of geomorphology and
234 sedimentary processes on seagrass habitat distribution. Further improvements to underwater
235 imaging can be achieved by utilising hyperspectral imagery, which can be used as a substitute for
236 in situ data for species-level identification (Bongiorno et al. 2018; Dumke et al. 2018). Improved
237 classification techniques are being tested for real-time classification of seagrass meadows using
238 underwater photography (e.g. Bonin-Font et al. 2018; Martin-Abadal et al. 2018). A summary of
239 studies that utilise underwater photography and videography is provided in **Appendix 1**.

240

241 **2.2.2 Seagrass remote sensing using aerial photographs and airborne hyperspectral data**

242 Airborne data, including aerial photographs and videography, have been widely used in
243 seagrass research ([Kendrick et al. 2000](#); [Pasqualini et al. 2001](#); [Frederiksen et al. 2004](#); [Lathrop
244 et al. 2006](#); [Fletcher et al. 2009](#); [Young et al. 2010](#)). Both passive (photographs, multispectral
245 and hyperspectral data) and LiDAR data can be obtained from airborne platforms.

246 Quantitative seagrass mapping using aerial photographs has been widely used (e.g.
247 [Ferguson et al. 1993](#); [Hernández-Cruz et al. 2006](#); [Orth et al. 2006b](#); [Fletcher et al. 2009](#); [Cuttriss
248 et al. 2013](#)), mainly because the visible wavelength undergoes less attenuation underwater than
249 other spectra ([Kirkman 1996](#)). Simple transformation techniques (e.g. Red Green Blue to
250 Intensity Hue Saturation) and image thresholding can be used to map seagrass areas from aerial
251 photographs ([Fletcher et al. 2009](#)). Aerial photographs have also been used for long-term
252 temporal and spatial monitoring of seagrass meadows. For example, [Hernández-Cruz et al.
253 \(2006\)](#) documented decadal spatial changes in seagrass meadows between 1937 and 2000 in
254 Puerto Rico. A number of classification techniques, such as on-screen digitizing ([Orth et al.
255 2006b](#); [Murdoch et al. 2007](#)), principal component analysis (PCA) ([Ferrat et al. 2003](#)), multi-
256 scale image segmentation and object-oriented image analysis, have been applied to digital
257 photographs for mapping the extent and density of seagrasses ([Lathrop et al. 2006](#)). The accuracy
258 of time-series seagrass mapping using aerial photographs depends on the mapping methods
259 applied ([Meehan et al. 2005](#)). On-screen digitizing, even though time consuming and depending
260 on the expertise of the researcher, can provide highly accurate seagrass maps if high resolution
261 aerial photographs are used. Even with low resolution aerial photography, the spatial distribution
262 pattern of seagrasses can be estimated ([Robbins 1997](#)), particularly where meadows are not
263 patchy. New image processing techniques, such as linear spectral unmixing, have been applied
264 recently on aerial photographs to improve seagrass mapping for identifying small seagrass

265 patches and masking the bare substrate (Uhrin and Townsend 2016). In shallow marine
266 environments where red light reaches the seabed, digital aerial photographs can also be used to
267 differentiate epiphytes (mostly red/brown) from seagrasses (mostly green) (Mount 2006, 2007).
268 At greater depths a combination of aerial photographs for shallow waters (0-20 m) and side-scan
269 sonar (SSS) for deep coastal regions (20-50 m) is recommended due to the differences in light
270 attenuation depth (e.g. Pasqualini et al. 1998; Leriche et al. 2006). Different types (colour, false
271 colour near-infrared, and black and white) of aerial photographs can also be used for seagrass
272 mapping in coastal areas with varying depths (e.g. Ferguson et al. 1993; Pasqualini et al. 2001;
273 Young et al. 2008, 2010).

274 Even though aerial photographs can be used to discriminate habitat features at a fine
275 scale, the lack of capacity to record in multiple bands (Hossain et al. 2015b) and dependency on
276 water quality (Hernández-Cruz et al. 2006) are drawbacks to the use of these data. Furthermore,
277 photometric variation inherent in aerial photography is a major source of misclassification when
278 seagrass mapping/classification relies solely on digital image processing techniques (Meehan et
279 al. 2005; Young et al. 201). Airplane-derived aerial photographs are also expensive to acquire, in
280 place of these a few recent studies (e.g. Barrel and Grand 2015) used cost-effective methods such
281 as low altitude, high resolution photographs from balloon-mounted digital camera platforms.
282 More recent studies have used cost and time-effective UAV-aerial photographs for seagrass
283 mapping (See section 2.2.6). However, historical records of seagrasses in many regions (e.g.
284 Rees 1993; Cunha et al. 2005; Meehan et al. 2005) are often only available from aerial
285 photographs, in which an error margin of up to 20% in quantifying the aerial extent of seagrasses
286 may still be acceptable where these are the only data available (Meehan et al. 2005).

287 Airborne platforms are commonly used for the acquisition of hyperspectral images (e.g.
288 AISA+, CASI-2, HyMap, Ocean PHILLS, PRISM), and these have been increasingly used for:
289 mapping the extent of seagrasses (e.g. Mumby et al. 1997; Dierssen et al. 2003; Bostater et al.
290 2004; Peneva et al. 2008); species level discrimination (e.g. Ferwerda et al. 2007; Phinn et al.
291 2008; Dierssen and Russel 2015); estimation of biomass and productivity (Hill et al. 2014); as
292 well as other factors including water column depth, water quality, bottom types (e.g. Garono et
293 al. 2004; Garcia et al. 2015; Hossain et al. 2015b) and spectral separation between seagrasses and
294 other bottom substrates such as algae (e.g. O'Neill et al. 2011; Pe'eri et al. 2016). Compared to
295 the use of a field spectroradiometer, airborne hyperspectral data has the advantage of greater
296 areal coverage. However, for mapping large areas of seagrass meadows, spaceborne
297 multispectral imagery is preferred due to the high cost per unit area for airborne derived imagery
298 (Hossain et al. 2015b). For mapping individual seagrass patches using airborne hyperspectral
299 data, some studies suggest that at least a 3m spatial resolution is required (e.g. Peneva et al.
300 2008). However, a number of recent studies (e.g. Phinn et al. 2008; Valle et al. 2015) obtained
301 species-level discrimination and biomass estimation of seagrass using CASI and CASI-2 images
302 with a spatial resolution of 4m alone or together with QuickBird-2 and Landsat data. **Appendix 2**
303 lists a number of studies published in the last two decades using airborne hyperspectral data for
304 seagrass studies and the mapping techniques used. A few recent studies have also used cost-
305 effective hyperspectral data from UAV platform (e.g. Uto et al. 2017; Manfreda et al. 2018),
306 which used pattern matching algorithms and vegetation indices for accurate seagrass mapping
307 improving bot resolution and repeatability.

308 A number of Vegetation indices, including various modified versions of the normalized
309 vegetation index (NDVI), have been developed for the automatic discrimination of seagrass

310 meadows (e.g. [Valle et al. 2015](#)). It is possible to use airborne hyperspectral data with proper
311 atmospheric correction to estimate detailed pigment composition of seagrass meadows using
312 vegetation indices, calibrated by hyperspectral field data (spectroradiometer) (e.g. [Bargain et al.](#)
313 [2013](#); [Hedley et al. 2016, 2017](#)). [Marcello et al. \(2018\)](#) observed that a combination of
314 hyperspectral and multispectral data increased the robustness and performance, respectively, of
315 seagrass mapping when maximum likelihood and support vector machine (SVM) methods were
316 applied.

317 Unlike spaceborne data, which has fixed sensor altitudes and orbits, airborne
318 hyperspectral data can have a variety of deployment altitudes and measurement geometry that
319 pose significant difficulties in dealing with atmospheric effects ([Castillo-López et al. 2017](#)),
320 particularly for shallow coastal waters with unknown aerosol properties, spatial heterogeneity in
321 the water column, and sensor artefacts ([Zhang et al. 2015](#)). [Zhang et al. \(2016\)](#) recommend an
322 iterative atmospheric correction in such cases, for monitoring short-term changes in shallow
323 water environments. However, accuracies in excess of 80% can be obtained without applying
324 any atmospheric correction methods to airborne hyperspectral data (e.g. [Zhang et al. 2013](#)).
325 Furthermore, water-depth correction algorithms using water absorption and scattering factors
326 have been found to improve seagrass mapping using hyperspectral data ([Lu and Cho 2012](#)).

327

328 **2.2.3 Spaceborne remote sensing data for seagrass mapping**

329 Spaceborne remote sensing platforms offer a cost-effective option where higher aerial
330 coverage is required, when mapping larger, monospecific and continuous seagrass meadows
331 ([Dekker et al. 2007](#)). In recent decades, a large number of sensors with a wide variety of spatial,
332 spectral and temporal resolutions offer various approaches to seagrass mapping. Even though,

333 spaceborne multispectral and hyperspectral data are constrained in highly turbid environments,
334 with limited applications in optically shallow waters, higher spectral resolutions (for
335 hyperspectral data) can reduce the number of mixed pixels and are relatively cheaper than
336 airborne derived data (Hossain et al. 2015b). More wavelengths in the visible region of the EMS
337 can greatly improve seagrass mapping. A summary of the most recent seagrass studies using
338 spaceborne multispectral and hyperspectral data with varying spatial resolution is provided in
339 **Appendix 3**.

340 A range of high-resolution multispectral spaceborne data is available from the early
341 1970s and most have the optical channels required for seagrass mapping (Wicaksono et al.
342 2017). Recently, a number of high spatial resolution (5 m to 50 cm resolution) multispectral
343 spaceborne data, such as SPOT-5 (e.g. Pasqualini et al. 2005), SPOT-7 (Siregar et al. 2018),
344 IKONOS (e.g. Mumby and Edwards 2002; Wabnitz et al. 2008; Howari et al. 2009; Pu and Bell
345 2017), GeoEye (Chayhard et al. 2018), WorldView-2 (Misbari and Hashim 2014; Reshitnyk et
346 al. 2014; Roelfsema et al. 2014; Adi 2015; Anggoro et al. 2016; Baumstark et al. 2016; Albert et
347 al. 2017; Halls and Costin 2016; Hoang et al. 2016; Koedsin et al. 2016; Manuputty et al. 2016;
348 Martin et al. 2016; Eugenio et al. 2017; Oguslu et al. 2018; Poursanidis et al. 2018), WorldView-
349 3 (e.g. Jadidi and Vitti 2016; Collin et al. 2017), QuickBird (Wang et al. 2007; Albert et al.
350 2017; Hisabayashi et al. 2018), KOMPSAT-2 (e.g. Kim et al. 2012, 2015; Matta et al. 2014a,
351 2014b; Choi et al. 2018), RapidEye (e.g. Matta et al. 2014a; Giardino et al. 2016; Li 2018;
352 Traganos and Reinartz 2018a) and PlanetScope (e.g. Traganos et al. 2017; Wicaksono and
353 Lazuardi 2018), have been used for mapping of seagrass meadows around the globe.

354 However, a large number of studies have used medium resolution satellite imagery, such
355 as Landsat series (e.g. Ferguson and Korfmacher 1997; Dahdouh-Guebas et al. 1999; Meyer

356 2008; Wabnitz et al. 2008; Roelfsema et al. 2009; Knudby et al. 2010; Meyer and Pu 2012; Pu et
357 al. 2012a, 2014; Blakey et al. 2015; Hossain et al. 2015a, 2015c; Kim et al. 2015; Chen et al.
358 2016; Millán et al. 2016; Müller et al. 2016; Ayustina et al. 2018; Geevarghese et al. 2018;
359 Hisabayashi et al. 2018; Topouzelis et al. 2018), ASTER (e.g. Pulliza 2004; Castaño-Gallego and
360 Lozano-Rivera 2006; Dahanayaka et al. 2012; Adi et al. 2013a; Wicaksono and Hafizt 2013;
361 Shofa 2014; Kim et al. 2015; Wicaksono et al. 2017), ALOS AVINIR-2 (e.g. Firdaus 2011;
362 Astuti et al. 2012; Adi et al. 2013b; da Silva et al. 2017), CBERS (e.g. Yang and Yang 2009;
363 Yang and Huang 2011), and Sentinel-2 (e.g. Topouzelis et al. 2016; Fauzan et al. 2017; Hafizt et
364 al. 2017; Thalib 2017; Thalib et al. 2017; Yanuar et al. 2017; Dattola et al. 2018; Fethers 2018;
365 Kovacs et al. 2018; Luo 2018; Traganos and Reinartz 2018b; Traganos et al. 2018a, 2018b;
366 Transon et al. 2018) and these are widely used for seagrass monitoring, particularly where long-
367 term datasets are available. Medium resolution satellite imagery can also be used to estimate
368 carbon stocks in an inexpensive way (Mashoreng et al. 2018). Similar to SPOT 5, ASTER data
369 also lack blue wavelength in the spectrum and hence coastal mapping capacity is limited
370 compared to the data mentioned above (Capolsini et al. 2003), particularly when applying
371 vegetation indices. Medium resolution multispectral imagery must be acquired at low tide for
372 accurate mapping of seagrass meadows.

373 Although the number of publications is limited, several studies have used low resolution
374 (>100m) spaceborne data, such as MODIS (e.g. Dierssen et al. 2010; Bargain et al. 2012; Adi et
375 al. 2013b; Downie et al. 2013; Barnes et al. 2014a; Petus et al. 2014a, 2014b, 2016, 2018; Tuya
376 et al. 2014; York et al. 2015; Phinn et al. 2017; Beck et al. 2018; Carlson et al. 2018;
377 Champenois and Borges 2018; Perez et al. 2018), AVHRR (e.g. Salas et al. 2000; Amela et al.
378 2007; Carlson et al. 2018), and MERIS (e.g. Lunetta et al. 2009; Roman et al. 2010; Adi et al.

379 [2013b](#); [Saulquin et al. 2013](#); [Matta et al. 2014b](#); [Roman and Dupouy 2014](#); [Zucchetta et al.](#)
380 [2016](#)), for large-scale seagrass research. These data were mostly used for understanding
381 biochemical, physical and other environmental variables associated with seagrass meadows (e.g.
382 [Amela et al. 2007](#); [Madrinan et al. 2010](#); [Peirano et al. 2011](#); [Madrinan and Fischer 2013](#); [York](#)
383 [et al. 2015](#); [Phinn et al. 2017](#)) rather than estimating their spatial extent due to the low spatial
384 resolution. Some studies (e.g. [Bargain et al. 2012](#)) used vegetation indices such as the ARVI
385 (Atmospherically Resistant Vegetation Index) developed by [Kaufman and Tanre \(1992\)](#) for
386 seagrass studies, which is derived from MODIS data. These vegetation indices were found to be,
387 on average, four times less sensitive to atmospheric effects when compared with NDVI ([Bargain](#)
388 [et al. 2012](#)).

389 Although it is more common to use airborne hyperspectral data for seagrass mapping,
390 spaceborne hyperspectral data, such as Hyperion (e.g. [Lee et al. 2005](#); [Pu et al. 2010, 2012](#); [Li et](#)
391 [al. 2012](#); [Yuan 2012](#); [Meyer 2013](#); [Pu and Bell 2013](#); [Zhao et al. 2013](#); [Kisevic 2015](#)) and
392 Hyperspectral Imager for the Coastal Ocean (HICO) ([Cho et al. 2013, 2014, 2016](#); [Garcia et al.](#)
393 [2014a, 2014b, 2015](#); [Adi 2015](#); [Huang and Cho 2016](#); [Jay et al. 2018](#)), have been employed for
394 detailed spectral characterization of seagrass meadows as well as the assessment of surrounding
395 environments. NASA's ongoing HypSPIRI mission is also expected to have a number of
396 applications in seagrass monitoring and mapping ([Lee et al. 2015](#)) with its 30 m spatial
397 resolution. A key limitation of the available hyperspectral data is their limited application in
398 highly turbid environments and/or deeper ocean areas ([Hossain et al. 2015b](#)).

399

400 **2.2.4 Seagrass studies using LiDAR, Laser scanners and Sonar**

401 In recent years airborne LiDAR and terrestrial laser scanners (TLS) have been used to
402 detect alterations to seagrass habitat characteristics, particularly 3D analysis (e.g. [Hannam and](#)
403 [Moskal 2015](#); [Corbi et al. 2018](#); [Collings et al. 2019](#)). Although costs are typically higher than
404 most satellite data, bathymetric LiDAR has good capabilities for high resolution seagrass
405 mapping due to its greater water penetration compared to higher wavelengths. Recently, sound
406 navigation and ranging (Sonar) systems, including multi-beam echosounders, have also been
407 employed for mapping and classification of seagrass meadows (e.g. [Komatsu et al. 2003](#); [Asada](#)
408 [et al. 2005](#); [Lefebvre et al. 2009](#); [Hamana and Komatsu 2016](#)), even though complex post-
409 processing algorithms are required for data extraction. Different algorithms for processing
410 LiDAR data for seagrass mapping include maximum likelihood classification ([Tulldahl and](#)
411 [Wikström 2012](#)) and object-oriented image classification ([Parrish et al. 2016](#)). [Parrish et al.](#)
412 [\(2016\)](#), using object-oriented methods, obtained a user's accuracy of 100% and producer's
413 accuracy of 82% in eelgrass mapping using LiDAR data. Using airborne Hawk Eye LiDAR,
414 even with the limited application in high turbidity areas, [Chust et al. \(2010\)](#) obtained an accuracy
415 between 84.5% and 92.1% in coastal habitat mapping. LiDAR data taken from a
416 tripod/vehicle/boat/underwater can also be used for small-scale seagrass surveys ([Hannam 2013](#);
417 [Hannam and Moskal 2015](#); [Corbi et al. 2018](#)). Terrestrial Laser Scanning devices provide an
418 accurate method for monitoring coastal areas that are subjected to erosion characterized by the
419 accumulation of seagrass berm ([Corbi et al. 2018](#)).

420 Airborne LiDAR data, usually taken from a helicopter, aeroplane or drone, have been
421 widely used for bathymetric surveys to identify the location and extent of seagrass meadows
422 ([Brock et al. 2006](#); [Wang and Philpot 2007](#); [Chust et al. 2008, 2010](#); [Valle et al. 2011, 2014](#);
423 [Collin et al. 2012](#); [Tulldahl and Wikström 2012](#); [Pan et al. 2014](#); [Zavalas et al. 2014](#); [Ishiguro et](#)

424 al. 2016; Parrish et al. 2016; Webster et al. 2016; Webster 2017; Collings et al. 2019). Chust et
425 al. (2008) observed higher accuracy in coastal habitat mapping using LiDAR data compared to
426 multispectral imagery. Full waveform bathymetric LiDAR can also be used to classify different
427 types of seagrasses (Pan et al. 2014). A combination of both LiDAR and multispectral data (e.g.
428 WorldView-2) further improves the accuracy of coastal habitat mapping (Chust et al. 2008;
429 Collings et al. 2019). Zavalas et al. (2014) used a combination of LiDAR and underwater
430 videography for mapping marine algal and seagrass communities. Webster et al. (2016) and
431 Webster (2017) used a MPIX RCD30 camera, which can be used to capture NIR and RGB
432 imagery co-aligned with LiDAR sensor (500 kHz for NIR and 35 kHz for Green) and can be
433 directly georeferenced. Multispectral LiDAR data has been proved its capabilities in assessing
434 structurally complex coastal habitat (Collin et al. 2012). Airborne LiDAR surveys have also been
435 used to map seagrass meadows studded with coral reefs (Brock et al. 2006) as well as for
436 modelling suitable habitat for seagrass meadows (Valle et al. 2011). Ishiguro et al. (2016) used a
437 combination of airborne LiDAR bathymetry data and aerial photographs for the successful
438 classification of seagrass meadows. Such studies using LiDAR data have helped the scientific
439 communities in understanding anthropogenic and climatic stresses on seagrass communities (Al-
440 Nasrawi et al. 2018) and projecting future distribution of seagrasses under global warming and
441 sea level rise (Valle et al. 2014). O'Hare et al. (2018) and Ventura et al. (2018) mentioned that
442 UAV's with LiDAR sensors have a high potential to improve plant-sediment studies in aquatic
443 environments, further developing on those in other coastal environments (Chadwick 2011; Ward
444 et al. 2013, 2016b).

445

446 **2.2.5 Seagrass remote sensing using Radar imagery**

447 Radar remote sensing has been used in a small number of studies, particularly for the
448 study of seagrass bed structure (Adolph et al. 2018; Gade et al. 2018). Although general
449 detection of seagrasses was nearly impossible, the elevated structures of sediments induced by
450 the seagrass cover can be mapped by the diffusely elevated backscatter values of Synthetic
451 Aperture Radar (SAR) (Adolph et al. 2018). Seagrasses enhance radar backscattering due to high
452 local surface roughness (even though they lay flat on the ground at low tide) (Gade et al. 2018),
453 and it is possible to apply a combination of structural analysis and unsupervised (ISODATA)
454 classification to SAR data for mapping seagrass beds (Adolph et al. 2018). Seagrass meadows
455 produce characteristic surface structures, different from green algae or diatoms, and merging
456 SAR data with multispectral data can be efficient in understanding the surface roughness
457 information and sediment types of seagrass meadows (Adolph et al. 2018). Combining Sentinel-
458 1 SAR with Sentinel-2 time series imagery and using NDVI statistic parameters showed an
459 improvement in seagrass mapping accuracy, with an overall accuracy of 77.7% and Kappa
460 coefficient of 0.75 (Luo 2018). Furthermore, bare soil can be separated from seagrass meadows
461 using SAR such as TerraSAR-X, which provides complimentary information to optical imagery
462 (Dehouck et al. 2011). Available SAR data for seagrass bed mapping include: TerraSAR-X,
463 TanDEM-X, COSMO-SkyMed, Sentinel-1 and Radarsat-2.

464

465 **2.2.6 Application of UAVs in seagrass research**

466 The use of UAVs for coastal ecosystem research (Figure 3), including seagrasses,
467 mangroves, saltmarshes, and coral reefs, is a new trend and a number of recent studies used
468 visible, thermal and infrared cameras on UAVs (Duffy et al. 2018; Konar and Iken 2018;
469 Villoslada et al. 2020). Notable advantages of using UAVs compared to aircraft, ships or satellite

470 platforms, are low operational costs, high operational flexibility and high spatial resolution
471 (Matese et al. 2015). Furthermore, UAVs are operated at a lower altitude and the disadvantage of
472 cloud cover, particularly in the tropics, while acquiring optical imagery can be avoided. Since the
473 images are taken from low altitudes, atmospheric absorption and other effects in a UAV derived
474 image are negligible compared to satellite data (Lomax et al. 2006). Although, images obtained
475 from UAVs have a clear advantage in terms of spatial resolution, the distinction of the species is
476 still only possible for exposed or shallow monospecific seagrass beds (Duffy et al. 2018). An
477 obvious disadvantage for UAV platforms compared to satellite platforms is the lower areal
478 coverage, particularly where meadows have monospecific species composition (high resolution
479 imagery is not required in this case) and detailed structural and morphological features are not
480 required. A list of the most recent seagrass studies utilising UAV platforms is given in **Appendix**
481 **4**.

482 The use of UAV platforms for seagrass mapping and monitoring has become more
483 sophisticated in recent years. Advances in technology are now focussing on light weight sensors
484 with multispectral, hyperspectral and LiDAR systems on UAVs (Uto et al. 2017; Manfreda et al.
485 2018). Multispectral satellite images combined with data taken from UAV produced high quality
486 maps of seagrass meadow in some cases. For example, Topouzelis et al. (2016) used a
487 combination of Sentinel-2 imagery and UAV-based data for seagrass mapping in Lesvos Island
488 in Greece. To avoid problems with surface water reflections, sun glint correction using polarised
489 filters can be utilised (Muslim et al. 2019) or image acquisition can be done in the morning and
490 evening (Chayhard et al. 2018).

491

492 **3. Seagrass research methods: traditional vs. remote sensing**

493 Seagrass meadow distribution mapping using remotely sensed data has predominantly
494 been undertaken using aerial photographs or satellite imagery (Ferwerda et al. 2007). However,
495 the previously discussed limitations of remote sensing (i.e. atmospheric effects and underwater
496 attenuation of EMR) must still be overcome.

497 Species-level discrimination of seagrasses using traditional methods is mainly conducted
498 by physical collection of samples and measuring morphological features (e.g. stem length,
499 flower), which can be costly and time consuming (Short et al. 2007). To undertake this using
500 remote sensing methods requires the inclusion of spectral features of pigments (chlorophyll-a
501 and chlorophyll-b) within visible wavelengths (Fyfe 2003), as the relative concentrations of
502 pigments (and hence the spectral reflectance) vary within species. Few studies (e.g. Fyfe 2003;
503 Pu et al. 2012; Casal et al. 2013) have utilized the differences in photosynthetic pigment content,
504 which in turn results in differences in the spectral reflectance for different seagrass species. One
505 of the difficulties in using this method, is the bias caused by the pigments contained in epiphytes
506 (Zimmerman and Dekker 2007) or other associated plant communities. However, high spectral
507 resolution data can be employed to solve this problem to some extent (Ferwerda et al. 2007).
508 Moreover, spectral reflectance of the same species at different wavelengths may vary with depth
509 and seasonality (Fyfe 2003). This indicates that traditional methods to collect and discriminate
510 seagrass samples must be done at the initial stage to create spectral libraries, which in turn can be
511 used to map species distribution. Spectral libraries can be created using hyperspectral data (e.g.
512 Pu et al. 2012; Casal et al. 2013) or in situ measurements using a spectroradiometer (e.g. Fyfe
513 2003; Thorhaug et al. 2007).

514 Robbins and Bell (1994) classified seagrass communities based on spatial structure and
515 pattern at three different levels as: (1) meadow, which has a contiguous areal distribution with

516 varying per cent cover composition, (2) bed, which has a contiguous areal distribution with
517 similar per cent cover composition, and (3) patch, which is a small and discrete clump of
518 seagrass or gap. Compared to species-level discrimination of seagrasses, this information (spatial
519 structure and pattern) can be obtained more easily with multispectral imagery (Lathrop et al.
520 2006).

521 Other traditional seagrass research methods include a number of constituents/steps that
522 can be done or improved using remote sensing, such as: seagrass abundance and depth
523 distribution, biomass, growth and production measurement, photosynthetic rates, algal epiphytes,
524 animal associates and seagrass decomposition (Short and Coles 2001; Krause-Jensen et al. 2004).
525 Additionally, a number of environmental parameters used in seagrass research, such as sediment
526 type and water quality of seagrass habitats, can also be evaluated using remotely sensed data
527 (Hossain et al. 2015b).

528

529 **3.1. Seagrass distribution, cover and biomass**

530 Seagrass meadows can be found in diverse environments with varying salinity, turbidity
531 and depth levels (Short and Coles 2001). Traditional methods of estimating seagrass distribution
532 use pre-recorded grid patterns or a combination of transects and sampling points (McKenzie et
533 al. 2001), which is time consuming with associated high costs (Short and Coles 2001). However,
534 mapping the occurrence of seagrasses can be done accurately with remotely sensed imagery. In
535 fact, seagrass distribution mapping using remotely sensed data has been undertaken since the
536 mid-20th century (Kelly 1980) using photographs taken from balloons, aircraft or a spacecraft,
537 suggesting that a range of acquisition platforms can be used in mapping seagrass parameters
538 (Hossain et al. 2015b). The success of remote sensing methods is highly dependent on the

539 spatial/spectral resolution of the data, accuracy (e.g. accuracy in georeferencing) and mapping
540 methods ([Short and Coles 2001](#)). Satellite images with high spatial resolution can be used to map
541 areas occupied by seagrasses more effectively than low spatial resolution data but the spatial
542 coverage of a high resolution data is often lower than that of low or medium resolution data (e.g.
543 single Landsat data scene covers 34,000 km² whereas a SPOT panchromatic tile covers only
544 60km². The same problems arise when using aerial photographs – the use of fine spatial
545 resolution aerial photographs requires a large number of frames where large areas are covered
546 ([Short and Coles 2001](#)). Seagrass distribution changes have been estimated using NDVI derived
547 from multispectral visible-infrared satellite data (e.g. Landsat, SPOT) calibrated using in situ
548 spectroradiometric data (e.g. [Barille et al. 2010](#)).

549 [Hossain et al. \(2015b\)](#) suggest that depth (e.g. intertidal, shallow subtidal, deep subtidal)
550 and water clarity (clear or turbid) are the principal factors that need to be considered when using
551 remote sensing to map seagrass parameters such as: distribution, percentage cover, species
552 composition and biomass. Data acquisition platform is also an important factor in mapping
553 seagrass parameters: space borne, aerial or boat ([Hossain et al. 2015b](#)).

554 There are many traditional ways of assessing seagrass cover, with the most common
555 method of non-destructive estimation being in-situ visual assessment of percentage cover using
556 predetermined quadrats ([Duarte and Kirkman 2001](#)). However, this methodology only includes
557 estimations of cover at specific points and does not evaluate the spatial variation of seagrass
558 cover within the meadow. In recent years, seagrass cover and change detection has been
559 estimated using a range of active and passive remote sensing systems with various resolutions
560 (high - [Pu and Bell 2017](#); [Chayhard et al. 2018](#); [Dattola et al. 2018](#); [Hisabayashi et al. 2018](#);
561 [Kovacs et al. 2018](#); [Su and Huang 2019](#); medium - [Yang and Huang 2011](#); [Shofa 2014](#);

562 [Wicaksono et al. 2017](#); [Ayustina et al. 2018](#); [Dattola et al. 2018](#); [Siregar et al. 2018](#) and low -
563 [Phinn et al. 2017](#); [Beck et al. 2018](#); [Carlson et al. 2018](#); [Petus et al. 2018](#)). Various active boat-
564 mounted acoustic sensors, e.g. SSS, side beam echo sounder (SBES), multi beam echo sounder
565 (MBES), and acoustic Doppler current profiler (ADCP) ([Warren and Peterson 2007](#); [Micallef et](#)
566 [al. 2012](#); [Montefalcone et al. 2013](#); [Greene et al. 2018](#); [McIntyre et al. 2018](#); [Held and Deimling](#)
567 [2019](#)), have also been used for mapping seagrass cover. Although, many studies have estimated
568 seagrass cover using remotely sensed data, the majority are still reliant on field measurements for
569 estimating shoot density and canopy height (e.g. [Gullstrom et al. 2006](#)).

570 Traditional seagrass biomass estimation involves both destructive and non-destructive
571 sampling of leaves and shoots within a number of quadrats ([Short and Coles 2001](#)). Destructive
572 sampling involves actual removal of the above (leaves and sheaths) and belowground (roots and
573 rhizomes) parts of the seagrass within each quadrat. On the other hand, non-destructive sampling
574 can be undertaken using photographs or video images of the quadrats with known biomass to
575 visually estimate biomass ([Short and Coles 2001](#)). As these methods involve extensive field
576 work with destructive sampling, newer methods have recently been applied using remote sensing
577 tools. Estimation of seagrass biomass can be done using multispectral/hyperspectral data,
578 particularly using the visible bands ([Armstrong 1993](#); [Phinn et al. 2008](#)) and their correlation
579 with the actual biomass of the seagrasses. Aboveground biomass can also be estimated using the
580 quantitative relationship between NDVI from SPOT imagery and dry weight of leaves ([Barille et](#)
581 [al. 2010](#)).

582 Recently, a large number of active remote sensing data from aircraft or UAVs have been
583 used for mapping seagrass cover. These airborne sensors are mainly LiDAR ([Tulldahl and](#)
584 [Wikström 2012](#); [Pan et al. 2014](#); [Zavalas et al. 2014](#); [Ishiguro et al. 2016](#); [Parrish et al. 2016](#);

585 Webster et al. 2016; Webster 2017; Collings et al. 2019), hyperspectral sensors like CASI-2,
586 PHILLS and HyMap (Dierssen et al. 2003; Garcia et al. 2015; Valle et al. 2015; Pan et al. 2016;
587 Castillo-López et al. 2017) or photographs (Frederiksen et al. 2004; Lathrop et al. 2006; Fletcher
588 et al. 2009; Young et al. 2010; Uhrin and Townsend 2016).

589

590 **3.2. Seagrass growth measurement**

591 Growth measurement in seagrasses at different levels (e.g. shoots, whole plant, and
592 population level) is best done by either direct (marking leaves, rhizomes and shoots) or indirect
593 (reconstruction of past growth from plant anatomical patterns) methods (Short and Coles 2001). In
594 addition to leaf and rhizome growth, additional calculations, such as stem growth, leaf
595 elongation, root growth, rhizome elongation, and shoot plastochrone interval may be required for
596 detailed growth measurements (Short and Coles 2001). Even though leaf marking methods have
597 been applied to a number of species (e.g. *Cymodocea nodosa*, *Enhalus acoroides*, *Halophila*
598 *ovalis*), a number of issues were reported related to the growth forms of various seagrasses
599 (Short and Coles 2001). Gaeckle and Short (2001) reported that comparison of leaf marking
600 methods in *Zostera marina* indicated that direct weight measurement of new tissue can introduce
601 significant errors in leaf growth. Furthermore, different growth forms of seagrasses may require
602 different marking methods (Short and Coles 2001). This method demands a number of logistic
603 facilities and hence is expensive in implementation.

604 Even though traditional methods for quantifying seagrass growth can provide very
605 accurate data, they are highly time consuming and difficult to produce large-scale quantitative
606 maps (Ferguson et al. 1993; Su and Huang 2019). Remote sensing methods can be applied to
607 indirectly measure growth patterns of seagrass meadows as they are modular plants exhibiting

608 clonal growth patterns (Baumstark 2018). Retrospective mapping of seagrass distribution can
609 provide accurate indirect assessment of trends in growth and decline. Time series analysis of
610 datasets, such as the Landsat series, has already proven to be effective in monitoring long-term
611 growth patterns of seagrasses (Lyons et al. 2010; 2013; Pu et al. 2014). For example, Vidyan
612 (2018) used a combination of Landsat data and Nearmap high resolution imagery for estimating
613 the seagrass growth pattern, extent and biomass in Cockburn Sound in Western Australia.
614 Baumstark (2018) used high resolution WorldView-2 data acquired in 2011 and 2013 to estimate
615 seagrass growth near the Indian River Lagoon in Florida. A combination of ALOS satellite
616 imagery acquired between 2008 and 2009 and in situ data collected between 2011 and 2012 have
617 been used by Rustam et al. (2013) for measuring growth rates and productivity dynamics of
618 *Enhalus acoroides* in Pari Island, Indonesia. However, it has to be noted that remote sensing
619 methods can only evaluate dynamic changes in seagrass extent/distribution/growth patterns,
620 actual growth rates cannot be measured.

621

622 **3.3. Photosynthesis in seagrass meadows**

623 Due to their photosynthetic activity, seagrasses are considered as important producers in
624 marine environment (Duarte and Chiscano 1999). Seagrass photosynthetic efficiency is also
625 considered as an indicator of broader coastal ecosystem health (Fonseca et al. 2003). Laboratory
626 measurement of seagrass photosynthesis is extremely intrusive, as the plants need to be removed
627 from their natural environment and a high degree of manipulation is required (Silva et al. 2009).
628 One of the oldest and simplest ways to quantify photosynthetic activity of plant is to measure the
629 O₂ evolved (Silva et al. 2009). In situ measurement of seagrass photosynthesis can be evaluated
630 using submersible pulse-amplitude modulated (PAM) fluorometers (e.g. Beer and Björk 2000).

631 [Silva et al. \(2008\)](#) used an infrared gas analysis (IRGA) technique for measuring photosynthesis
632 in seagrasses by a continuous measurement of dissolved CO₂ flux using incubation chambers
633 connected to an analyser at the surface. Even though in-situ measurement of seagrass
634 photosynthesis is not as exhaustive as laboratory analysis, and control of experimental conditions
635 is limited, these at least provide results representative of natural conditions (Silva et al. 2009).

636 One of the possible remote sensing methods to measure photosynthesis in seagrass
637 meadows is by studying the relationships between spectral reflectance (using a spectroradiometer
638 or other sensors) and photosynthesis, which has been applied to terrestrial plants (e.g. [Richardson
639 and Berlyn 2002](#)). However, underwater light attenuation properties may restrict the applicability
640 of this method. This method can also be restricted by depth and the physical and chemical
641 properties of water. [Zimmerman \(2003\)](#) proposed a two-flow bio-optical model for predicting
642 downwelling spectral irradiance distributions, which is a robust tool for the measurement of
643 photosynthesis in seagrasses as a function of water quality, depth, canopy structure, and leaf
644 orientation. A remote sensing approach for the indirect measurement of photosynthesis in
645 seagrasses can be based on the changes in $p\text{CO}_2$ /acidification, salinity or chlorophyll
646 concentration, which can be obtained from airborne/spaceborne sensors (discussed in section 4).
647 Acoustic methods for photosynthesis measurement are preferred by some authors (e.g. [Hermand
648 2004a, 2004b](#)). [Wilson et al. \(2012\)](#) observed that high frequency acoustic methods perform
649 better in estimating seagrass photosynthesis compared to low frequency. The photochemical
650 response index (PRI), which is a measure of photosynthetic radiation use efficiency (PRUE)
651 ([Thorhaug et al. 2006](#)), is another option to be explored further for photosynthesis measurement
652 of seagrasses using remote sensing.

653

654 **3.4. Seagrass associated species (epiphytes and epifauna)**

655 Epiphytes are commonly associated with seagrasses and can be an indicator of excessive
656 nutrients in the marine ecosystem (Teng et al. 2013) having a negative impact on seagrass
657 environments. Epiphytes are traditionally assessed by sampling individual shoots or visual
658 estimation within quadrats (Kendrick and Lavery 2001). Quantifying algal epiphytic biomass is
659 important in assessing changes in biomass due to eutrophication (Kendrick and Lavery 2001).
660 The preferred method for determining epiphyte biomass is dry weight and ash free dry weight
661 (Kendrick and Lavery 2001). Studies on epiphyte productivity are used to determine the relative
662 contribution of epiphytes to total meadow production and to understand the contribution of
663 epiphyte production to higher trophic levels (Pollard and Kogure 1993).

664 In general, species or community level discrimination of seagrass meadows and
665 associated vegetation, even though difficult, is theoretically possible using hyperspectral data
666 (Mutanga and Skidmore 2004). For example, Dierssen and Russel (2015) used hyperspectral data
667 (Portable Remote Imaging Spectrometer – PRISM) for the assessment of the hyperspectral
668 properties of the macroalgae *Sargassum* and the seagrass *Syringodium filiforme* in Greater
669 Florida Bay. Drake et al. (2003) developed a model that yielded a robust and positive
670 relationship between epiphyte biomass and its absorption of photons and a strong negative
671 relationship between epiphyte biomass and spectral photosynthesis of seagrass hosts.

672 Field sampling methods for the study of seagrass-associated fauna, such as those species
673 living within the bottom sediments (infauna) and those living in the canopy or seabed (epifauna),
674 include: hand-held corers, suction samplers, deep water sampling, and grabs and box corers for
675 infauna and: small beam net to suction samplers and deep water samplers for epifauna (Guzman
676 and Grizzle 2001). Large and mobile epibenthos, including fish, crabs and shrimps), require

677 more sophisticated mechanical assistance such as adequately sized boats and underwater cameras
678 ([Edgar et al. 2001](#)).

679 Remote sensing methods for studying seagrass-associated fauna are more complex than
680 those for seagrass-associated flora. [Teng et al. \(2013\)](#) used hyperspectral data from a
681 spectrophotometer to investigate epifauna cover on seagrass blades using the N-FINDR
682 algorithm for spectral analysis. Indirect methods could include using remotely sensed data to
683 evaluate changes in the foliar structure of seagrasses as a result of invertebrate grazing ([Nakaoka](#)
684 [2005](#)), which can be differentiated from foliar changes resulting from other factors such as
685 natural decomposition based on spectral properties.

686

687 **4. Secondary applications of remote sensing in seagrass research**

688 In addition to the direct measurement of seagrass distribution, cover and biomass, remote
689 sensing applications have been widely applied to measure water quality, light penetration,
690 sediment type and other physical parameters (e.g. temperature, salinity, pH, water currents,
691 waves and turbulence) in seagrass meadows ([Dekker et al. 2007](#); [Daud et al. 2019](#); [Gumusay et](#)
692 [al. 2019](#)). Knowledge concerning environmental conditions within seagrass meadows is
693 important to understand the spatial distribution and the relationship with environmental variables
694 ([Roelfsema et al. 2013](#); [Daud et al. 2019](#); [Lima et al. 2020](#)). Remote sensing data from multiple
695 sources can be used to analyse some of the aforementioned environmental variables. For
696 example, [Nezlin et al. \(2005\)](#) used SeaWiFS imagery to analyse the extent of sediment plumes.
697 Seagrass growth is highly dependent on sea surface temperature, suspended sediment and
698 salinity (in order), with optimal seagrass growth occurring in ideal temperature and salinity
699 conditions, dependent on species, with low suspended sediment concentrations ([Daud et al.](#)

700 [2019](#)). Radar remote sensing is another option for measuring environmental variables, such as
701 ocean currents and tides, wave height, surface wind speed and direction, which are important for
702 seagrass communities ([Hossain and Hashim 2019](#)).

703

704 **4.1. Suspended sediments**

705 Water quality and other environmental variables, including suspended and dissolved
706 sediment concentrations, have been monitored in seagrass environments using remote sensing
707 data by applying linear and non-linear algorithms ([Ferwerda et al. 2007](#); [Devlin et al. 2015](#); [Han
708 et al. 2016](#); [Petus et al. 2016](#)). Current satellite imagery have a high enough spatial and spectral
709 resolution for monitoring sediment plumes, which is a key factor influencing light availability in
710 coastal and estuarine regions based on surface reflectance differences due to varying turbidity
711 conditions ([Barnes et al. 2015](#)). The analysis of coastal waters, however, is complex, due to the
712 presence of organic and inorganic sediments, microorganisms, phytoplankton and water currents
713 ([Pozdnyakov et al. 2005](#)). Landsat data has been widely used in shallow water remote sensing for
714 monitoring suspended sediments (e.g. [Harrington et al. 1992](#); [Brivio et al. 2001](#); [Thiemann and
715 Kaufmann 2002](#); [Barnes et al. 2015](#); [Veettill and Quang 2018](#)), while other spaceborne data with
716 comparable spatial resolution to Landsat, such as ASTER, have also been used for the estimating
717 suspended solids in coastal waters (e.g. [Kishino et al. 2005](#)). Low resolution satellite data such as
718 AVHRR ([Ruhl et al. 2001](#)) or MODIS ([Hu et al. 2004](#); [Devlin et al. 2012](#); [Schroeder et al. 2012](#);
719 [Petus et al. 2014b](#); [Kumar et al. 2016](#)) or VIIRS ([Han et al. 2016](#)) have been used successfully
720 for analysing suspended sediment concentrations in estuarine and coastal water environments.
721 Most of these studies were based on the establishment of empirical relationships between in situ
722 observations and remote sensing data for estimating suspended solids. Airborne microwave data

723 can also be employed for estimating sediment plumes in marine environments. For example,
724 [Burrage et al. \(2003\)](#) used airborne data from the scanning low frequency microwave radiometer
725 (SLFMR) for mapping plumes and salinity by applying regression methods in the Great Barrier
726 Reef. [Zhang et al. \(2002\)](#) used a combination of Landsat and spaceborne microwave data (ERS2
727 SAR data) for surface water quality estimation in the Gulf of Finland. Aerial images, combined
728 with satellite data, have also been used in some studies (e.g. [Devlin and Brodie 2005](#); [Devlin and](#)
729 [Schaffelke 2009](#)) for estimating the extent of sediment plumes. For small areas with detailed
730 observations on turbidity and sediment plumes in seagrass environments, even though expensive,
731 high resolution airborne data such as portable remote imaging spectrometer (PRISM) can be
732 used effectively ([Fichot et al. 2016](#)). However, for understanding sediment dynamics at the
733 seabed, seagrass sediment coring is recommended where specific horizons can be dated (e.g.
734 ^{210}Pb , ^{14}C) ([Ward et al. 2014](#)).

735

736 **4.2. Light penetration**

737 One of the variables that determines the percentage of light penetrating the water column
738 and available for seagrasses is the diffuse attenuation of solar light ($K_d \text{ m}^{-1}$), which can be
739 measured using remote sensing data such as MODIS imagery ([Barnes et al. 2014a](#)). Spaceborne
740 ocean colour sensors, such as the Coastal Zone Color Scanner (CZCS) and SeaWiFS, can be
741 used to estimate light penetration in the water column based on the blue-to-green reflectance
742 ratio ([Gattuso et al. 2006](#)). However, in practice, such relationships may not be straight forward
743 in coastal waters with high suspended particle concentrations (two main contributors of light
744 attenuation in coastal waters are phytoplankton and suspended particles). [Hill et al. \(2014\)](#) used

745 airborne hyperspectral data for the evaluation of light availability and biomass of seagrass
746 environment in Saint Joseph's Bay in Florida.

747

748 **4.3. Ocean temperature**

749 For the measurement of sea surface temperatures (SST), which is an important variable
750 for seagrass habitat, spaceborne datasets such as AVHRR (1 km) or MODIS (250 m) imagery
751 can be used (Esaias et al. 1998), even though these data have a coarse spatial resolution. SST
752 measurements using split window techniques have been found to be superior to that of using
753 single spectral channel or a pair of windows in separate spectral regions (Stramma and Cornillon
754 1986) by reducing the impact of atmospheric transmittance and water vapour content in the
755 algorithms (Sobrino et al. 1993). Non-linear SST algorithms using AVHRR provide similar
756 accuracies under a wide range of environmental conditions (Li et al. 2001). Another widely used
757 satellite data is from the Geostationary Operational Environmental Satellites (GOES 8/9)
758 launched by NOAA (Wu et al. 1999). For SST measurements, ship-based sensors such as
759 Atmospheric Emitted Radiance Interferometer (AERI) have been used with accuracy less than
760 0.1°C (e.g. Smith et al. 1996). It is worth to note that SST retrieval from space in most of the
761 ocean areas are sampled from polar orbiting satellites at most twice a day and that surface diurnal
762 variability studies rely on the extrapolation of *in situ* measurements at depth (Gentemann and
763 Minnett 2008). However, the ocean surface responds to changes in fluxes of heat and momentum
764 rapidly and the diurnal variability at the ocean surface can be quite different from heating at
765 depth (Gentemann and Minnett 2008). Scanning radiometers, such as the Advanced Along-Track
766 Scanning Radiometer (AATSR) and Advanced Microwave Scanning Radiometer (AMSR-E),
767 have been observed to have accuracies comparable to in situ data (O'Carroll et al. 2008),

768 although AATSR only functions well in cloud-free environments, whereas microwave
769 measurements can be used in all weather conditions (Hosoda 2010). Even though microwave
770 remote sensing studies have higher accuracies compared with infrared measurements, sea surface
771 wind correction still remains a problem (Hosoda 2010). For regional applications with diurnal
772 cycle SST information, NASA has developed a Short-term Prediction and Research Transition
773 (SPoRT) program based on 1km MODIS data (Haines et al. 2007).

774

775 **4.4. Ocean salinity**

776 Under a changing climate, variations in ocean salinity occur due to the melting of polar
777 ice caps and sea ice (Wadhams and Munk 2004; Stammer 2008) that may affect seagrass
778 meadow health and photosynthetic abilities (Sandoval-Gil et al. 2012) from regional to global
779 scales. It has been reported that the spectral reflectance of seagrass meadows have been altered
780 due to changes in salinity (Thorhaug et al. 2006), which can be explored using remotely sensed
781 data. Optical and microwave remote sensing can be used to estimate salinity in marine
782 environments. For example, Daud et al. (2019) estimated salinity conditions and suspended
783 sediments in Banten Bay in Indonesia using Sentinel-2 data by applying simple band math
784 algorithms and the normalized mean value error of the results were less than 10% for all the
785 estimated variables (salinity and suspended sediments). Geiger (2011) applied ANN methods to
786 MODIS data for ocean salinity measurements in the mid-Atlantic. Salinity from satellite data can
787 be estimated indirectly based on the coefficient of coloured dissolved organic matter (a_{CDOM})
788 (Bai et al. 2013). Ocean colour monitoring satellite sensors, such as SeaWiFS, have been used
789 successfully for ocean salinity mapping (Binding and Bowers 2003). Microwave data have also
790 been widely used for salinity mapping in seagrass environments. The European Space Agency

791 (ESA) has designed and launched (November 2009) a satellite sensor – Soil Moisture and Ocean
792 Salinity (SMOS) – specifically for mapping soil moisture and ocean salinity (Font et al. 2013).
793 Some researchers (e.g. Hernandez et al. 2015) mentioned that the SMOS instrument has a better
794 performance for salinity mapping ($r = 0.57$) than NASA’s Aquarius ($r = 0.52$), which has been
795 designed to understand the oceanic thermohaline circulation related to interannual climate
796 variability (Koblinsky et al. 2003). Airborne microwave radiometers, such as Scanning Low-
797 Frequency Microwave radiometer (SLFMR) and the Salinity, Temperature, and Roughness
798 Remote Scanner (STARRS), perform better in mapping sea surface salinity, especially in
799 estuarine and coastal environments (Klemas 2011).

800

801 **4.5. Coastal ocean acidification**

802 Ocean acidification has been linked to increases in photosynthetic rates in seagrasses due
803 to the increase in concentration of aqueous CO_2 as a primary carbon source, and dissolved
804 inorganic carbon species as bicarbonate ions (Garrard and Beaumont 2014; Repolho et al. 2017).
805 Although some studies suggest an increase in organic carbon sequestration rates by seagrasses
806 under acidic conditions (Palacios and Zimmerman 2007; Hall-Spencer et al. 2008; Fabricius et
807 al. 2011; Russell et al. 2013; Garrard and Beaumont 2014; Mazarrasa et al. 2018) others report a
808 substantial decrease (Martínez-Crego et al. 2014; Repolho et al. 2017).

809 Furthermore, recent studies (e.g. Unsworth et al. 2012; Hendricks et al. 2014; Koweek et
810 al. 2018; Bergstrom et al. 2019) have suggested that the presence of seagrass communities can
811 mitigate the negative effects of ocean acidification on marine ecosystems. Several studies have
812 used remote sensing methods to monitor ocean acidification (Balch et al. 2007; Gledhill et al.
813 2008) and Sun et al. (2012) applied five variables (air-sea CO_2 fluxes, total alkalinity, suspended

814 calcite (particulate inorganic carbon), particulate organic carbon and calcification rates) from
815 remote sensing data to indirectly estimate ocean acidification (Takahashi et al. 2014). In
816 addition, since ocean acidification is directly linked to global calcification rates, estimation of
817 calcification rates from satellite data can also be used as a proxy for ocean acidification (Balch et
818 al. 2007; Moses et al. 2009). Recent studies, such as Land et al. (2015) and Sabia et al. (2015)
819 discussed the application of salinity information from satellite data for the assessment of ocean
820 acidification.

821

822 **4.6. Water currents and waves**

823 Ocean currents influence pollination processes, sedimentation rates and sediment
824 geochemistry of seagrass ecosystems (Koch and Verduin 2001). Seagrass directional
825 characteristics depend on wave direction – seagrass leaves tend to flap back and forth in wave-
826 dominated habitats, whereas the leaves tend to bend in the direction of tidal waves in tide-
827 dominated habitats (Koch and Verduin 2001). Turbulence affects carbon and nutrient transfer
828 and dispersion of pollen, seeds and spores in seagrass habitats (Koch and Verduin 2001). Air-sea
829 turbulent fluxes are important in the exchange of momentum, heat and gas between atmosphere
830 and ocean (Bourassa et al. 2010). Therefore, monitoring ocean currents and waves using remote
831 sensing platforms can be useful in understanding seagrass distribution, reproduction and
832 sedimentary cycles.

833 Ocean surface currents can be measured indirectly from spaceborne data using physical
834 models involving the variables such as sea surface height, surface winds and sea surface
835 temperature (Dohan and Maximenko 2010). Other methods, such as using surface velocity
836 measured from buoys transmitted to satellite sensors or tracking of surface features and use of

837 Doppler shift in radar fields from SAR, have also been used (e.g. [Dohan and Maximenko 2010](#)).
838 High frequency (HF) radar systems, such as Ocean Surface Current Radar (OSCR), provide
839 periodic, two-dimensional vector estimates of surface currents ([Chapman et al. 1997](#); [Shrira et al.](#)
840 [2001](#); [Klemas 2012](#)). Furthermore, microwave data can also be used to estimate ocean currents
841 indirectly from other variables such as SST ([Isern-Fontanet et al. 2006](#)). [Klemas \(2012\)](#)
842 mentioned that ocean currents from infrared remote sensing data can be studied by tracking the
843 movement of thermal and colour features in the ocean.

844 Microwave remote sensing provides information on ocean surface roughness, showing
845 surface waves by analysing backscatter radiation ([Goldstein et al. 1994](#); [Pearce and Pattiaratchi](#)
846 [1997](#)). In addition to spaceborne data, airborne sensors can also be used to study ocean surface
847 waves. For example, [Dugan et al. \(2001\)](#) used an airborne optical sensor called Airborne Remote
848 Optical Spotlight System (AROSS), which can also be mounted on a UAV, for measuring
849 surface waves from time-series imagery.

850

851 **4.7. Marine eutrophication using remote sensing**

852 Nutrient pollution is a key driver of eutrophication and algal blooms within coastal
853 waters ([Lapointe et al. 2015](#)). Eutrophication influences seagrass meadows in different ways, for
854 example, [Raffaelli \(1999\)](#) observed that seagrasses in Scottish coastal areas were replaced by
855 green algae following eutrophication. Increases in green algae reduce light penetration in coastal
856 waters thereby reducing seagrasses photosynthetic capabilities and growth rates ([Ferreira et al.](#)
857 [2011](#)). In other words, seagrasses were observed to have been replaced by fast growing
858 competitors like microalgae and macroalgae during the initial stages of eutrophication ([Waycott](#)
859 [et al. 2009](#)).

860 Eutrophic conditions can be studied using remotely sensed data by examining the growth
861 of phytoplankton (by estimating the chlorophyll content) (Bagheri and Dios 1990). Lee et al.
862 (2004) found that the ratio of leaf nitrogen to leaf mass can be considered as a sensitive and
863 consistent indicator of early eutrophication. Measurement of nitrates, phosphates and other
864 nutrients can also be estimated using spaceborne and airborne data (Veetil and Quang 2018).
865 Cauwer et al. (2004) used spring mean and maximum chlorophyll-a concentrations from satellite
866 data (MODIS, SeaWiFS, MERIS) for estimating the eutrophication status with coastal waters in
867 Belgium. Large-scale marine trophic conditions, such as in the Mediterranean Sea, have been
868 studied using SeaWiFS (Acker et al. 2005; D'Ortenzio and d'Alcala 2009) or MODIS data
869 (Allen et al. 2008) or a combination of both (Banks et al. 2012). Airborne multispectral or
870 hyperspectral data, such as AVIRIS, can be effectively used for retrieving marine water
871 constituents and estimating eutrophication (Bagheri et al. 2005). For small-scale eutrophication
872 measurement based on chlorophyll-a data from space, Landsat TM data has been used since
873 1980s (e.g. Bagheri and Dios 1990). Coastal Zone Color Scanner Experiment (CZCS), which is
874 the first spaceborne instrument specifically made for the measurement of ocean colour, has been
875 used for eutrophication monitoring in coastal areas based on mapping the extent of algal blooms
876 (Blondeau-Patissier et al. 2014).

877 The key challenges in using remote sensing data for eutrophication studies is the
878 improvement of algorithms applied and refining the detection limits in different oceanic and
879 coastal environments (Blondeau-Patissier et al. 2014). It is essential to consider the effects of
880 water temperature, turbidity, solar radiation and bathymetry to understand spatio-temporal
881 patterns of algal blooms and eutrophication (Blondeau-Patissier et al. 2014). In order to estimate
882 coastal eutrophication from remote sensing datasets, proper cloud masking schemes need to be

883 applied to improve the accuracy (Banks and Melin 2015). For example, Barnes et al. (2014b)
884 aggregated the Landsat TM 30 m pixels to 240 m pixel to increase the signal-to-noise ratio and
885 applied a MODIS-like atmospheric correction approach for estimating water quality, which was
886 found to have improved the accuracy.

887

888 **5. Discussion**

889 Seagrass ecosystems are important coastal environments currently under threat
890 throughout their global range (Orth et al. 2006a; Waycott et al. 2009; Jones and Unsworth 2016;
891 Unsworth et al. 2017; Jones et al. 2018). As they cover relatively large areas, sometimes poorly
892 accessible for field research, remote sensing is an alternative tool for mapping and monitoring
893 these ecosystems (Pham et al. 2019). This review has highlighted the significant contributions of
894 remote sensing datasets and various techniques applied to seagrass research, while comparing
895 their use and accessibility to traditional, in-situ, methods. Ecologists and managers can use the
896 information acquired by high spatial resolution maps to provide invaluable information about
897 seagrass ecology and environmental health to be used for the management of protected areas and
898 understanding of biodiversity, functioning, services, and future sustainability of seagrass,
899 particularly in areas with reported seagrass decline (Koedsin et al. 2016; Giardino et al. 2017;
900 Pham et al. 2019).

901 Overall, it has been demonstrated that high spatial resolution data can be used to improve
902 seagrass classification accuracy (Sagawa et al. 2010; Meyer et al. 2010; Lu and Cho 2012;
903 Tamondong et al. 2013; Saunders et al. 2015; Barrell et al. 2015; Pham et al. 2019). However,
904 medium to high spatial resolution data, such as the Landsat time-series, have been most widely
905 used for monitoring these ecosystems at larger scales (Meyer et al. 2010; Knudby and Nordlund

906 [2011](#); [Ferreira et al. 2012](#); [Borfecchia et al. 2013](#); [Hogrefe et al. 2014](#); [Kim et al. 2015](#)).
907 Moreover, active remotely-sensed data, such as SAR and LiDAR, have been used to ensure
908 higher performance in mapping and monitoring of seagrass ecosystems than some low resolution
909 space borne data ([Hogrefe et al. 2014](#); [Duffy et al. 2018](#)), while multi-temporal high spatial
910 resolution images have been used to monitor changes in specific areas ([Tuxen et al. 2011](#); [Pu and](#)
911 [Bell 2017](#)). The incorporation of multi-resolution and multi-source (SAR, multispectral, and
912 LiDAR) data may be used as a tool to improve accuracy ([Pham et al. 2019](#)). For example,
913 research efforts have been made to expand the use of optical sensors, such as multispectral and
914 hyperspectral datasets, in combination with different traditional methods for mapping and
915 monitoring seagrass ecosystems ([Qiu et al. 2019](#); [Giardino et al. 2019](#)). However, more attention
916 seems to have been paid to the more advanced, or the hybrid, remote sensing methods using a
917 combination of multi-source and multi-temporal datasets ([Pham et al. 2019](#)).

918 Although multi-spectral imagery has emerged as a popular dataset for seagrass mapping,
919 the limited number of spectral bands may lead to a low accuracy of single species detection
920 ([Lyons et al. 2011](#); [Paulose et al. 2013](#)). For this reason, hyper-spectral imagery has been widely
921 combined with physical-based models and various classification algorithms to improve the
922 accuracy of seagrass detection in complex water environments ([Koedsin et al. 2016](#)). Generally,
923 the semi-analytical method using hyper-spectral imagery allows a higher mapping accuracy than
924 the empirical approach ([Roelfsema et al. 2014](#)). However, it requires an intensive spectral library
925 of different bottom curves as the input for the classification algorithm, which implies an
926 expensive field sampling and storage of the library in the case of large-area and mixed bottom
927 type site monitoring ([Roelfsema et al. 2014](#); [Traganos and Reinartz 2018c](#); [Duffy et al. 2018](#);

928 Gereon et al. 2018). In addition, hyper-spectral sensors usually have a small coverage and
929 require on-demand flights for specific geographic regions (Pham et al. 2019).

930 It should be noted, however, that the remote sensing processes vary depending on the
931 environmental conditions of the study area (i.e., depth, tidal level, etc.), highlighting the need to
932 conduct prior field research to appropriately interpret and validate remote sensing data obtained
933 (Short and Coles 2001; Howari et al. 2009; Phinn et al. 2008; Lyons et al. 2011; Koedsin et al.
934 2016). In the near future, more advanced sensors, such as SAR and LiDAR, and novel machine
935 learning approaches and deep learning methods should be used for mapping and monitoring
936 seagrass ecosystems. Therefore, focus should be placed on the development and selection of
937 state-of-the-art machine learning algorithms for mapping and monitoring in future studies.

938

939 **6. Conclusions and future research**

940 Despite the fact that seagrass meadows function as primary producers, mitigate climate
941 change through carbon sequestration, and provide a habitat for a wide variety of marine plant and
942 animal species, there has been a decline in global seagrass cover and hence it is important to
943 understand meadow location, distribution and health in a cost-effective way with a greater
944 geographical cover.

945 Recently, a large number of active and passive remote sensing approaches have been
946 used to estimate various parameters associated with seagrass communities, such as plant cover
947 and habitat quality. Such methods can provide relevant and long-term data for analysing seagrass
948 ecosystem change. Seagrass ecosystem information that can be evaluated using remote sensing
949 are: presence of seagrass, extent, species composition, seagrass-associated communities, stem
950 health, biomass, temporal ecosystem changes, ecosystem services, and environmental quality.

951 Various types of remote sensing data that can be used to analyse seagrass ecosystem data include
952 terrestrial and underwater photography/videography, aerial photographs and airborne
953 hyperspectral data, spaceborne multispectral and hyperspectral data, LiDAR, Laser scanners,
954 Sonar, Radar, and data from UAVs/AUVs.

955 There are also a number of environmental parameters that influence seagrass ecosystem
956 location and ecological health that can be evaluated using remotely sensed data, in particular:
957 suspended sediments, light penetration, ocean temperature, ocean salinity, coastal ocean
958 acidification, and marine eutrophication.

959 Even though remote sensing can be used for a wide variety of applications in seagrass
960 research, there are limitations to be overcome regarding spatial, spectral and radiometric
961 resolution and environmental factors such as depth, turbidity, phytoplankton and pollution.
962 Unlike terrestrial plant ecosystems, seagrass communities are often submerged and hence there
963 are limitations to apply landscape techniques using remote sensing methods to seagrasses. While
964 using optical data, only visible wavelengths pass through water column and can be used for
965 mapping seagrass communities and both atmospheric correction and water column attenuation
966 coefficients must be applied. Furthermore, spectral discrimination of seagrass communities using
967 optical data becomes difficult with increase in depth due to absorption and scattering.

968 A combination of multi-type, multi-source of remotely sensed datasets combining remote
969 sensing and field data are most effective in understanding the broader aspects of seagrass
970 ecosystems. For example, a combination of multispectral optical data and SAR data can be
971 helpful in discriminating seagrass meadows and green algae based on surface roughness
972 information and sediment types. Recent advancements in data and decreases in costs of UAVs
973 and AUVs provide an excellent opportunity to obtain fine scale data concerning seagrass

974 meadow structure, function, location, and species diversity, although this is best combined with
975 field data. In order to improve data quality from UAVs, polarized filters can be used for sun glint
976 correction. High spatial resolution hyperspectral data from spaceborne sensors with fixed sensor
977 altitude and orbit may reduce the cost of image acquisition and processing compared to airborne
978 data having a variety of deployment altitudes and measurement geometry. Various classification
979 algorithms and physical-based models are being developed resulting in improved accuracy for
980 seagrass mapping. There has historically been a paucity of studies on seagrasses compared with
981 related ecosystems such as mangroves, salt marshes or coral reefs that offer a similar range of
982 ecosystem services. However, in light of the growing interest in seagrasses, particularly
983 concerning ecosystem service provision it should be noted that there are a range of remote
984 sensing techniques and platforms that can be used to study these vital ecosystems. Variations in
985 estimations of extent and distribution of seagrasses are much greater than those for related
986 coastal systems. The authors, therefore would like to encourage a range of studies from extent
987 and distribution mapping, to carbon sequestration and storage to ecosystem health utilising a
988 range of methods, including those highlighted in this review, in order to fill the gap in knowledge
989 of seagrass systems at local, regional and global scales.

990

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998

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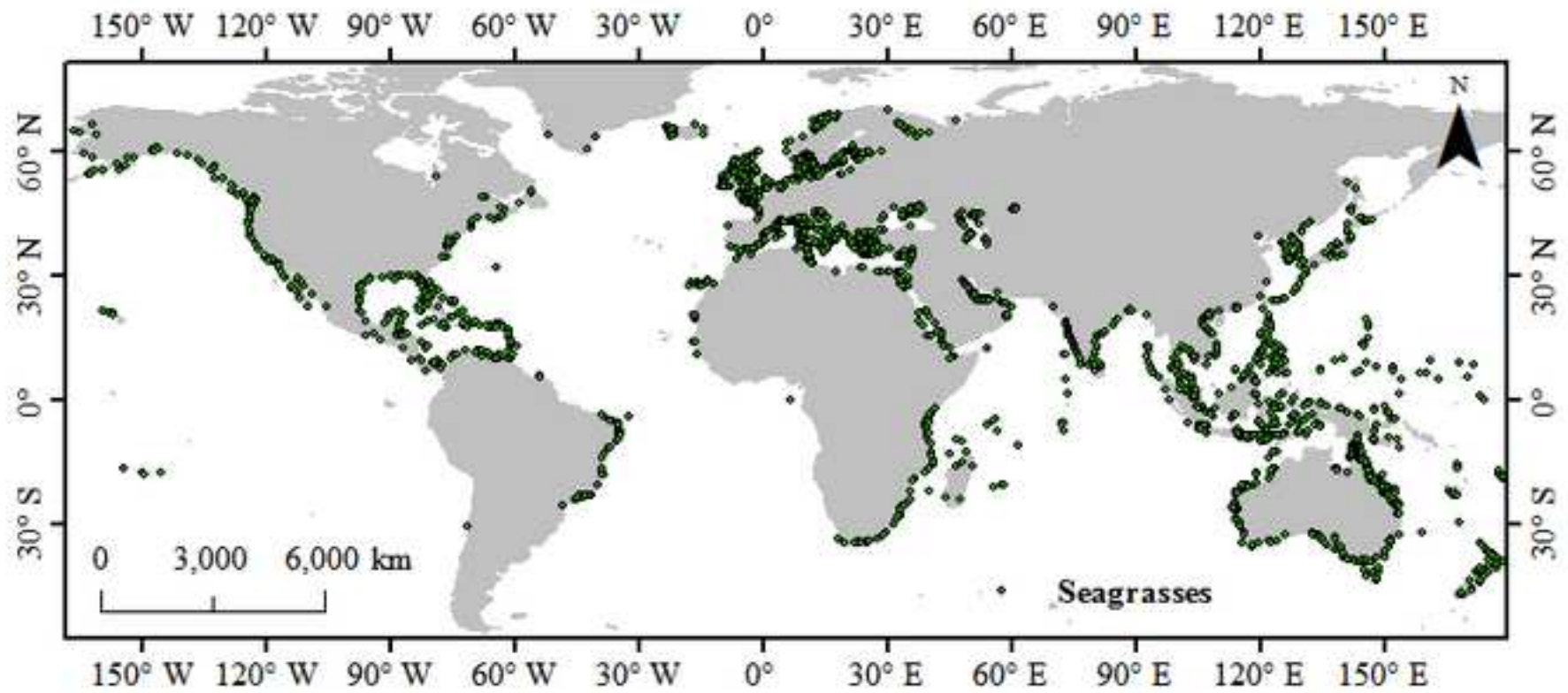


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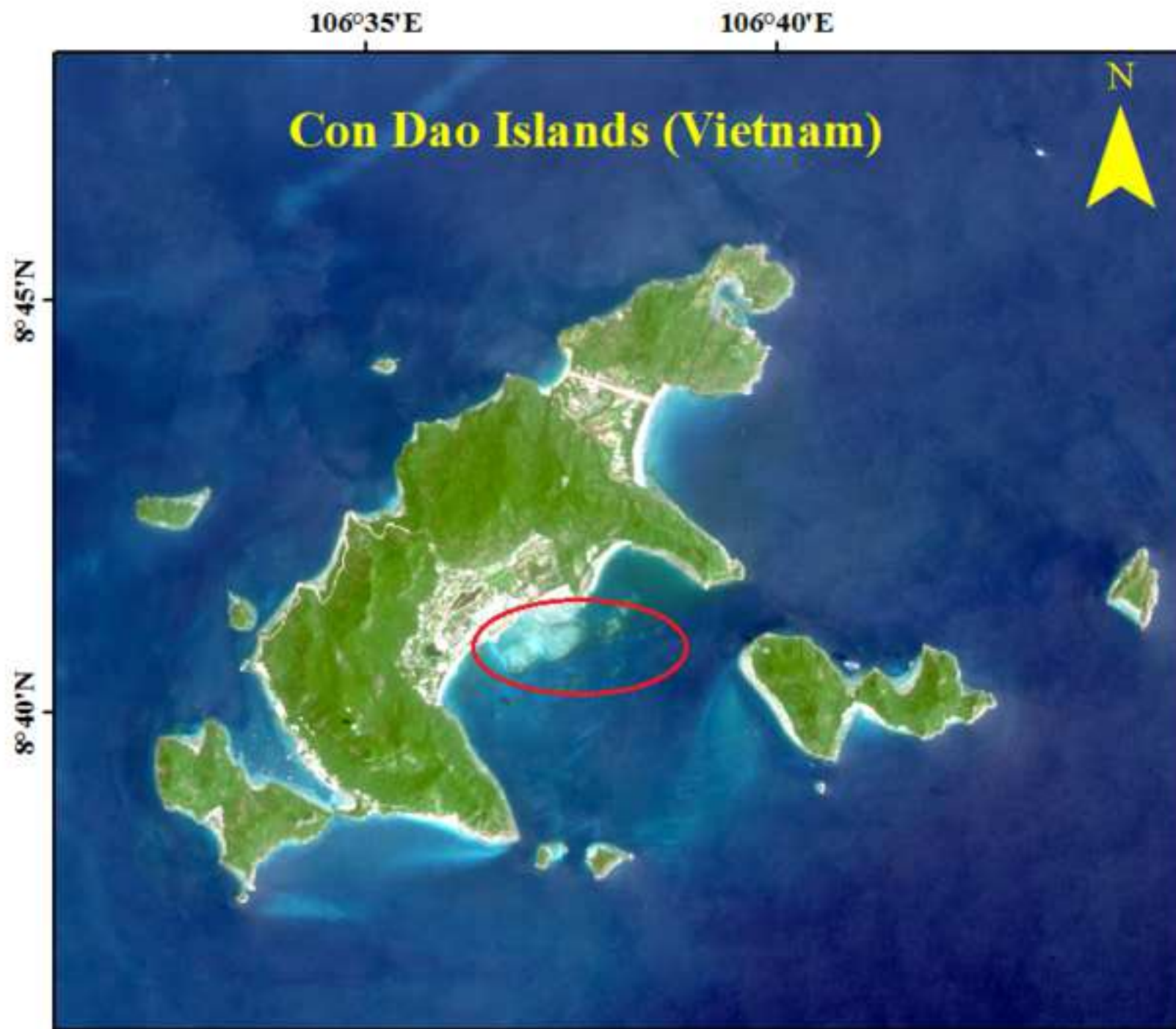


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