Planning for seaweed aquaculture in Tasmania: A preliminary evaluation of biophysical potential and co-location with existing aquaculture

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Executive Summary

The cultivation of seaweed (macroalgae) is emerging in Australia and anticipated to grow in the future. In response to this interest in industry growth, the Tasmanian Government has identified a need to better spatially resolve the biophysical requirements and potential for marine-based (coastal) seaweed aquaculture in waters off Tasmania. The intent is to inform local planning and site selection to optimize production when needed. It is also meant to eventually better understand how seaweed aquaculture could be embedded with existing marine industrial activities, such as existing aquaculture and wastewater treatment, and non-industrial activities, such as ecosystem restoration.

This report addresses biophysical conditions, constraints, and co-location with existing aquaculture, as an initial indicator of potential, of 15 selected seaweed taxa of interest determined by the Tasmanian Government. The report is divided into four sections:

- Description of the contemporary distribution of seaweed taxa of interest in Tasmania;
- Assessment of key biophysical attributes that may limit the siting of aquaculture of seaweed taxa of interest, when known;
- Preliminary statewide spatial assessment of key biophysical attributes, including the identification of data sources and gaps;
- Synthesis of ecological distribution and preliminary spatial assessment in nine discrete areas around Tasmania to inform government planning. This includes considerations for co-location with existing aquaculture.

KEY FINDINGS

The contemporary distribution of seaweed taxa of interest differed significantly with some very common (e.g., *Ecklonia radiata*) and rarely observed (e.g., *Cladophora vagabunda*) taxa. The west coast of Tasmania is poorly sampled and represents a clear data gap. The southeast of Tasmania is the most 'species-rich' region, with all 15 seaweed taxa of interest observed. However, sampling effort is also greatest in this region.

Biophysical constraints for the siting of coastal seaweed aquaculture in Tasmania includes water temperature, exposure, light regime, and nutrient availability. Constraints on water temperature and exposure are best understood for the taxa of interest, while information on minimum nutrient and light requirements is sparser. Four taxa of interest are sensitive to temperature: *Lessonia corrugata, Macrocystis pyrifera, Durvillaea potatorum*, and *Ecklonia radiata*.

Data sources for key biophysical variables are available for a preliminary statewide assessment, albeit sometimes as proxies and at a coarse resolution. Coastal nutrient availability is a key data gap; it is filled here by using hydrography coupled with land use. Water temperature and light regime are estimated with remote sensing (satellite) data (presented as monthly averages), while a proxy for exposure – openness derived from the geography of the coastline – is determined at regular intervals along the coastline.

RECOMMENDATIONS

Relevant information is collated in this report with the purpose to inform future planning for the development of coastal seaweed aquaculture in Tasmania. However, data gaps remain. Recommendations to fill these gaps to further support planning include:

- Resolving minimal and optimal conditions for growth for taxa of interest, ideally by focusing on fewer taxa. It is noted this information is lacking for several taxa of interest, and should include operational needs, which are not adequately captured by natural distributions.
- Identify priority areas of interest based on this research or other sources and conduct a biophysical assessment at a higher spatiotemporal resolution, with available data. Eventually, this would also include socio-economic context to inform planning.

Introduction

The cultivation of seaweed (macroalgae) is emerging in Australia. The industry is currently valued at AUD$ 3 million – primarily from wild harvest – but is expected to grow in future decades, with a potential valuation of AUD$1.5 billion by 2040 (Kelly 2020). This is anticipated to require a significant expansion in the cultivation of seaweeds in Australian marine waters, including Tasmania. Given its rich native diversity of seaweed (750 recorded species; Hurd et al. 2023) and research capacity, efforts and interest to commercially cultivate seaweeds in Tasmania has grown in recent years.

In response to this interest in industry growth, the Tasmanian Government has identified a need to better spatially resolve the biophysical requirements and potential for marine-based seaweed aquaculture in Tasmanian waters. This is intended to inform local planning and site selection to optimize production when needed, and eventually, to better understand how seaweed aquaculture could be embedded with existing marine industrial activities, such as existing aquaculture and wastewater treatment, and non-industrial activities, such as ecosystem restoration, in Tasmania. Despite growing interest in offshore cultivation (detailed in Visch et al. 2023), marine-based seaweed/macroalgae aquaculture is currently anticipated to occur in the coastal zone. Similar exercises, albeit with different approaches and context, have been conducted elsewhere in Australia (South Australia; Wiltshire and Tanner 2020), and overseas (e.g., Tasnim et al. 2024, Visch et al. 2020).

In the present study, biophysical potential is addressed by determining the contemporary Tasmanian distribution of seaweed taxa of interest, identifying environmental constraints that may limit the siting of aquaculture sites, and identifying data sources and gaps to spatially map these constraints at an appropriate scale and resolution. Importantly, this study does not aim at this stage to optimize the siting of specific cultivated species. Rather, it aims to support the identification of areas of interest that would later benefit from more detailed studies on site suitability.

Tasmania currently hosts the largest aquaculture industry in Australia with a value of AUD$ 1.21 billion in 2021-22, dominated by salmonids (Tasmanian Agri-Food Scorecard 2021-22, Department of Natural Resources and Environment Tasmania). It is therefore important to better understand how existing aquaculture activities could benefit or support an emerging seaweed aquaculture industry. Co-location can occur at varying degrees: from integrated sites (e.g., integrated multi-trophic aquaculture) to neighbouring leases to local or regional areas being developed as part of a joint development strategy, for example to share resources and enhance planning efficiency. In Tasmania, ongoing research and development is examining co-location of salmonid aquaculture with seaweed. While integration is not the focus of this study, relevant information is provided for later research to further examine the co-location potential of seaweed and salmonid aquaculture in Tasmania.

This study focuses on 15 seaweed taxa of interest, two of which are not endemic to Tasmania (Table 1). This suite of species was provided by the Tasmanian Government to support this study, and may not at the time of writing represent the full suite of species with potential for commercial marine-based aquaculture in Tasmania.

Table 1. Seaweed taxa of interest as specified by the Department of Natural Resources and Environment Tasmania. '*' denotes introduced/invasive species. '[]' denotes other names used in Section 1 datasets.

Latin name	Section 1	Type
Asparagopsis armata	*Asparagopsis armata*	Red
Caulerpa brownii	*Caulerpa brownii*	Green
Caulerpa geminata	*Caulerpa geminata* [*Caulerpa sedoides var. geminata*]	Green
Chaetomorpha billardierii	*Chaetomorpha billardierii*	Green
Chaetomorpha coliformis	*Chaetomorpha coliformis*	Green
Cladophora vagabunda	*Cladophora vagabunda*	Green
Codium fragile subsp. novae-zelandiae	***Codium fragile*[1]**	Green
Codium harveyi	*Codium harveyi*	Green
Durvillaea potatorum	*Durvillaea potatorum*	Brown
Ecklonia radiata	*Ecklonia radiata*	Brown (Kelp)
*Grateloupia turuturu**	*Grateloupia turuturu**	Red
Lessonia corrugata	*Lessonia corrugata*	Brown (Kelp)
Macrocystis pyrifera	*Macrocystis pyrifera* [*Macrosystis angustifolia*; *Macrocystis spp.*]	Brown (Kelp)
Ulva lactuca var. lacinulata	***Ulva spp.*[1]** [*Ulva rigida; Ulva australis*]	Green
*Undaria pinnatifida**	*Undaria pinnatifida**	Brown (Kelp)

1. Records of these species were not present in the datasets. Alternatives are used to estimate biophysical suitability.

This study is divided into four sections:

SECTION 1 describes the **contemporary distribution** of seaweed taxa of interest in Tasmania (Table 1). This section collates existing datasets from databases as well as species occurrences from the literature to coarsely determine the distribution of taxa of interest using contemporary (i.e., since 2012) and historical (since the early 1980s) observations. A compilation of observed taxa of interest among nine geographic regions in Tasmania is presented.

SECTION 2 determines the **key biophysical attributes** relevant to the siting of seaweed aquaculture in Tasmania. While optimizing site selection is a core aspect of marine spatial decision-support science, this section rather aims in a first instance to identify limitations that would warrant consideration before identifying and developing sites. These limitations can be either existing or anticipated, for example due to environmental change. This section relies on a literature review to establish range of conditions – if known – for taxa of interest occurring in Tasmania, Australia or overseas (with a preference for temperate ecosystems). This section also uses when appropriate the occurrence data from Section 1 to further determine the ecological niche of taxa of interest.

SECTION 3 presents a **preliminary statewide spatial assessment** of key factors relevant to the siting of seaweed aquaculture in Tasmania. This section uses available datasets – often at a coarser resolution than desired – to characterize biophysical conditions in Tasmanian waters. Given the need for the statewide characterization, some datasets stem from satellite remote sensing technology. In some cases, data from proxies are provided. Data gaps are detailed, as well as potential avenues for further research to fill these data gaps in specific areas of interest and at a higher spatiotemporal resolution. Finally, the spatial configuration of existing aquaculture is considered in this section.

SECTION 4 summarizes findings from previous sections and presents a **synthesis** of ecological distribution and preliminary spatial assessment in Tasmania, divided in nine regions. This section aims to collate available information by region to guide further research in examining key biophysical factors – and eventually socio-economic factors – at a relevant scale.

Recommendations are included at the end of the study to guide future work, as needed.

SECTION 1: Contemporary distribution of seaweeds of interest in Tasmania

1.1 RATIONALE

The overall aim of this section is to better understand the contemporary distribution of 15 seaweed taxa of interest in Tasmanian waters (see Table 1). This effort is meant to guide aquaculture siting in relation to wild populations (where relevant). This information is relevant to managers who may not want species cultivated outside of their natural range, for example to avoid unintended biological pollution in recipient ecosystems and protect genetic diversity. Further, the section seeks to enhance our understanding of the biophysical drivers of the distribution of the seaweed taxa of interest, including for non-endemic species where data allows. Finally, the section identifies data gaps for poorly-resolved ecological distribution, or areas likely to be under-sampled.

1. 2 METHODS

DATA SOURCES

Available occurrence data of species of interest was extracted from the primary scientific literature, grey literature (technical reports), and available databases (Table 2). The study area included Tasmanian waters, and the temporal range extended from 1984 to 2021. Only *in-situ* observations with a survey date were considered. A summary of the data sources is shown in Table 2.

Some occurrence records were duplicated across different data sources, therefore pointing to the same observations. To address this, sites less than 10m apart were labelled as the same site, and at each site, observations occurring at the same time (survey date) were considered to be the same observation.

Codium fragile var. novae-zelandiae did not occur in the dataset. However, occurrences of *Codium fragile* are included here. Similarly, occurrences of *Ulva lactuca var. lacinulata* did not occur; instead, we use records of *Ulva spp. Ulva rigida and Ulva australis* to estimate biophysical suitability in Tasmania.

A total of 4931 observations of seaweed taxa of interest were collated across 568 unique sites in Tasmania (Fig. 1). Out of the 568 sites, 214 have been visited since 2012. Most sites are distributed along the south, east and north coast of Tasmania, with a clear data gap for most of the west coast.

SYNTHESIS

Occurrences were collated and synthesized across nine regions covering the coastline of Tasmania: southeast (Southeast Cape to Tasman Island), Tasman Peninsula (Tasman Island to Cape Paul Lamanon), mid-east coast (Cape Paul Lamanon to Cape Sonnerat), north east coast (Cape Sonnerat to Cape Portland), north coast (Cape Portland to Cape Grim), west coast (Cape Grim to Port Davey), south coast (Port Davey to Southeast Cape), King Island, and the Furneaux Group.

Table 2. Data sources and observations used to estimate the contemporary distribution of seaweed species of interest in Tasmania.

DATASET	DATA SOURCE	TEMPORAL RANGE	SPATIAL UNIT	NUMBER OF OBSERVATIONS [UNIQUE SITES]	SPECIES/TAXA OF INTEREST OBSERVED
Conditions of rocky reef communities around Tasmania: algal surveys	IMAS Data Portal (and available on the Australian Ocean Data Portal; aodn.org.au)	1992-95; 2006-07	Site (SITE_CODE)	1523 [281]	*Ecklonia radiata; Durvillaea potatorum; Lessonia corrugata; Macrocystis pyrifera* [*Macrosystis angustifolia*; *Macrocystis spp.*]; *Caulerpa brownii; Codium fragile; Asparagopsis armata; Undaria pinnatifida; Codium harveyi; Chaetomorpha billardierii; Chaetomorpha coliformis; Ulva spp.; Caulerpa sedoides var. geminata*
Video surveys of long spined sea urchin (Centrostephanus rodgersii) barrens habitat, eastern Tasmania [algal counts]	IMAS Data Portal (and available on the Australian Ocean Data Portal; aodn.org.au)	2001-02	Transect (Transect_ID)	290 [153]	*Ecklonia radiata; Durvillaea potatorum; Lessonia corrugata; Macrocystis pyrifera*
National Reef Monitoring Network	Australian Ocean Data Portal (aodn.org.au)	1992-2021	Site	4272 [304]	*Caulerpa geminata, Caulerpa brownii, Durvillaea potatorum, Ecklonia radiata, Lessonia corrugata, Macrocystis pyrifera, Asparagopsis armata, Chaetomorpha billardierii, Undaria pinnatifida, Codium fragile, Codium harveyi, Chaetomorpha coliformis, Grateloupia turuturu, Ulva spp., Ulva rigida, Ulva australis*
Occurrences from the literature	n = 12 (See Appendix 1 for details)	1984-2020	Occurrences where geographic coordinates and survey date were provided	265 [116]	*Ecklonia radiata, Asparagopsis armata, Macrocystis pyrifera, Durvillaea potatorum, Caulerpa geminata, Lessonia corrugata, Undaria pinnatifida, Chaetomorpha coliformis, Caulerpa brownii, Codium fragile, Codium harveyi; Ulva spp.*
Atlas of Living Australia	ala.org.au	2018	--	1	*Cladophora vagabunda*

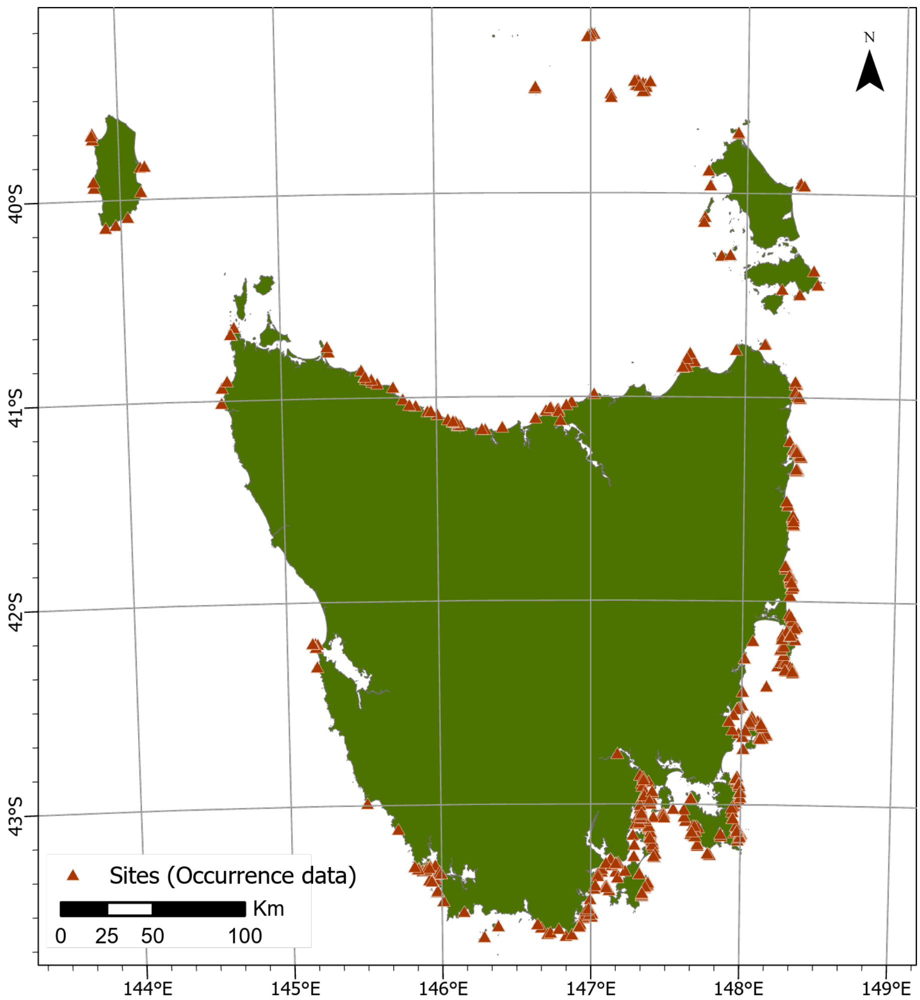


Figure 1. Sites of occurrence data collected between 1984 and 2021 for the seaweed taxa of interest in Tasmania (n = 568).

1.3 Results

Most taxa were observed for most of the time period (1984 – 2021) with few exceptions, such as *Grateloupia turuturu*, an introduced species, and *Cladophora vagabunda* (only one record in 2018; Table 3). Some species were observed at many sites: *Ecklonia radiata* (501 sites), *Lessonia corrugata* (166 sites), *Caulerpa brownii* (170 sites), *Macrocystis pyrifera* (164 sites), and *Durvillaea potatorum* (145 sites). Occurrence data (by site) for each species is provided in Appendix 2.

Relatively more taxa were recorded in the southeast (all 15 taxa) and the mid-east coast (14 taxa; Fig. 2). The Tasman Peninsula and west coast each had the lowest number of recorded taxa (7); however, few sites on the west coast were included in this study (11) so it is likely this number may be under-estimated. The north-east coast, south coast, and north coast each had either 11 or 12 species (Fig. 2).

Table 3. Number of observations and sites, and temporal range of observations of taxa of interest around Tasmania.

Taxa	Number of sites	Number of observations	Temporal range
Asparagopsis armata	74	167	1994 - 2021
Caulerpa brownii	173	571	1992 – 2021
Caulerpa geminata	92	448	1992 – 2021
Chaetomorpha billardierii	21	51	1994 – 2020
Chaetomorpha coliformis	63	105	2006 – 2021
Cladophora vagabunda	1	1	2018
Codium fragile	67	82	1992 – 2019
Codium harveyi	34	101	1994 – 2021
Durvillaea potatorum	145	319	1984 – 2021
Ecklonia radiata	505	1852	1984 – 2021
Grateloupia turuturu	5	7	2009 – 2020
Lessonia corrugata	167	403	1992 – 2021
Macrocystis pyrifera	164	343	1984 – 2021
Ulva spp.	95	368	1992 – 2021
Undaria pinnatifida	36	113	1992 - 2019

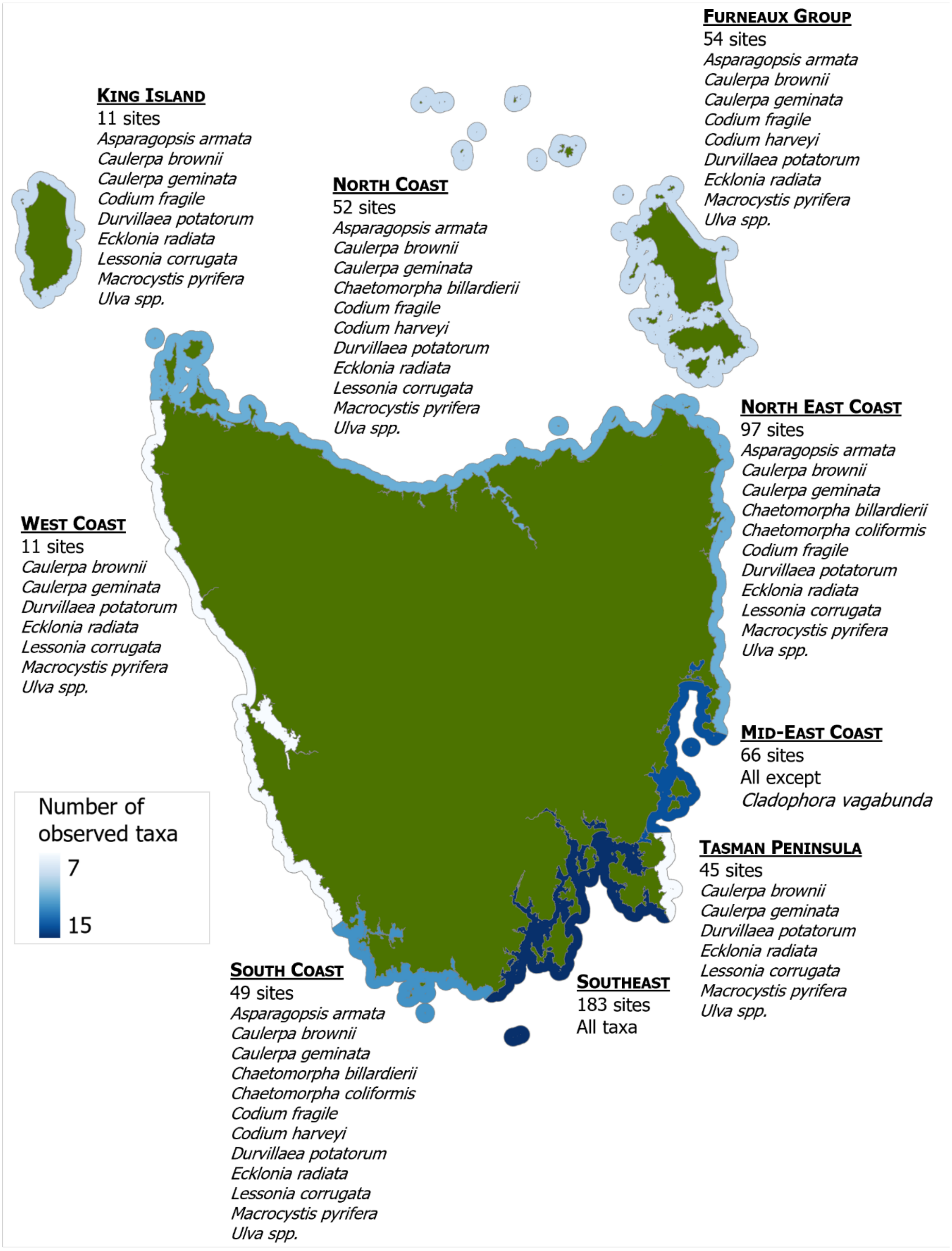


Figure 2. Summary of occurrences recorded in this study for 15 seaweed taxa of interest in Tasmania (1984 – 2021). Occurrences for individual taxon are presented in Appendix 2. Areas are for visualization purposes only.

SECTION 2: Key biophysical attributes

2.1 RATIONALE

The distribution and abundance of seaweeds is influenced by wave exposure (hydrodynamics), suitable substrate, water temperature, light regime (specifically, photosynthetically available radiation – PAR), nutrient availability, and other aspects of water chemistry (e.g., dissolved CO_2). (see Hurd et al. 2014). Defining ecological niches in wild populations are relevant but not sufficient to understand conditions for aquaculture. Other considerations related to biophysical conditions of a given geographic area that could influence operations include for example seabed depth, distance to shore, weather patterns (e.g., for ongoing maintenance and site access), production levels for financial sustainability, biosecurity and influence of pathogens, and interspecific interactions in multi-species cultivation systems. It is important to include such considerations; however, given the level of practical experience required to address these, they may best be defined on a taxon-by-taxon basis at higher spatial resolutions within restricted geographic areas.

Here, the focus is on biophysical variables that could be included in a spatially-explicit (GIS-based) decision-support system to support holistic site selection for aquaculture (as per Sanchez-Jerez et al. 2016, Falconer et al. 2019). The aim is to describe known biophysical ranges for the 15 seaweed taxa of interest based on field observations or laboratory studies for these biophysical variables, and hence identify potential constraints or limits to cultivation in Tasmania. This exercise is not meant to optimize the allocation of space, 'site suitability' for taxa of interest, or estimate production potential.

When determining biophysical constraints, it is critical to identify the relevant life-history stage for each species or taxon of interest that would be cultivated at sea. This differs among taxa of interest and a comprehensive review of established or emerging cultivation methods is beyond scope for this study. Instead, the focus is on environmental conditions meant to inform cultivation at sea.

As a preliminary assessment, biophysical variables under consideration include **water temperature**, **exposure**, **light regime**, and **nutrient availability**. This is based on variables known to impact the natural distribution of taxa of interest in Tasmania (e.g., Butler et al. 2020a, Hurd et al. 2023, James et al. 2024).

2.2 METHODS

INSIGHTS FROM OCCURRENCE DATA

Occurrence data for the 15 seaweed taxa of interest were recorded at 568 unique sites in Tasmania (Section 1, Fig. 1). This provided an opportunity to further infer biophysical ranges for the taxa of interest. Given the significant temporal variability of observations (1984-2021), only the geographic static exposure index of 'openness' was calculated to further examine the relationship of each taxon of interest to exposure (based on Hill et al. 2010).

Openness is an index of exposure reflecting the geography of the coastline. Openness is calculated by measuring the total distance (up to 650 km) to the nearest land mass along 48 bearings around a point of interest. The index is expressed as a fraction [0-1] based on the maximum theoretical total distance (here: 48 x 650 km) and is used as a proxy to contrast sheltered environments (relatively lower values) against exposed environments (relatively higher values). Openness was calculated at all 568 unique sites and summarized across taxa of interest based on their occurrence. Importantly, openness is a simple index of exposure. More refined analyses would include wind patterns, fetch and bathymetry for more specific exposure regimes at given sites of interest.

LITERATURE REVIEW

A systematic literature review was conducted to determine the environmental range under which the taxa of interest occur for the biophysical variables of interest: water temperature (thermal tolerance), exposure (hydrodynamics and wave action), light availability (e.g., photosynthesis-irradiance relationships), and nutrient availability (e.g., minimum concentration of nutrients). The review was based on the primary scientific literature and grey literature (reports), when relevant.

EXPERT OPINION

Experts at the Institute for Marine and Antarctic Studies were consulted to identify the realized ecological niche of the taxa of interest. Experts were asked to estimate the temperature range at which taxa occur, the relationship with exposure (exposed, moderate, sheltered or mixed), and their nutrient-level requirements when known. It was highlighted that interactions among these factors are important to consider when assessing biophysical suitability. Our focus was however to identify limitations to the taxa's distribution, not at this stage optimize siting for growth.

1.3 RESULTS

Calculations of openness indices across all 568 sites (range: < 0.001 – 0.49) revealed a gradient in biophysical niche occupied by the 15 taxa of interest (Fig. 3). Species observed at the most 'exposed' sites (mean: 0.16-0.20) included *Durvillaea potatorum* (mean: 0.20) and *Lessonia corrugata* (mean: 0.16). Species observed at mostly moderate sites with some occurrences at exposed sites (mean: 0.06-0.09) included *Ecklonia radiata, Macrocystis pyrifera*, *Caulerpa brownii,* and *Grateloupia turuturu*. Species mostly found at moderate sites (mean: 0.02-0.03) included *Codium fragile, Ulva* spp., and *Chaetomorpha coliformis*. Species predominantly found at sheltered sites (mean: 0.01-0.02) included *Asparagopsis armata, Undaria pinnatifida, Codium harveyi, Chaetomorpha billardierii,* and *Caulerpa geminata*. *Cladophora vagabunda* was observed at only one (sheltered) site.

Known biophysical ranges based on the literature review, expert opinion and insights from occurrence data (openness index of exposure) are summarized in Table 4. Importantly, this review may not be comprehensive – i.e., other sources may exist but have not been uncovered in this exercise.

Biophysical range could not be determined for all taxa of interest for all biophysical variables. Notably, information on nutrient requirements and nutrient uptake kinetics (and preference) is poorly resolved in this study, as well as requirements for light regime. The latter data gap has been noted by Hurd et al. (2023) for Tasmanian seaweed species. Information on these variables was restricted to taxa already developed for aquaculture (e.g., *Undaria pinnatifida)*.

Relationships with exposure and currents is available for all taxa, at a minimum derived from insights from the occurrence data in this study and expert opinion. Similarly, information on thermal tolerance is available for most taxa, with some exceptions. Based on this information, at least four taxa are likely to be stressed by warmer temperature (i.e., > 20-22°C): *Durvillaea potatorum* (restricted to southeast Australia; Visch et al. 2023), *Ecklonia radiata* (no sporophytes developed above 22°C; Mabin et al. 2019), *Lessonia corrugata* (critical thermal limit ~22°C; expert opinion), and *Macrocystis pyrifera* (critical thermal limit for adult sporophyte: ~20°C; expert opinion).

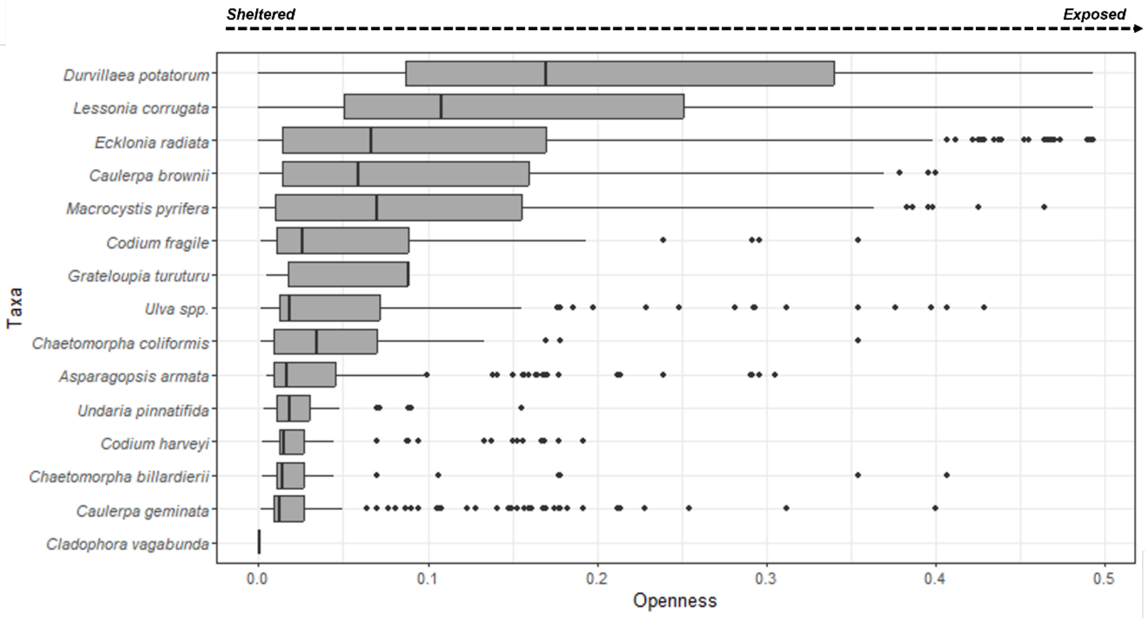


Figure 3. (Boxplots) Range of openness indices for each taxon of interest based on 568 sites in Tasmania. Number of observations per taxon is provided in Table 3.

Nutrient requirements were the least readily defined in the literature, particularly for production and in the context of this study identifying constraints on seaweed aquaculture. For a few species, e.g., *Ecklonia radiata* and *Macrocystis pyrifera*, laboratory experiments provided estimates of minimum (lower) estimates of nutrient (nitrate) concentrations. However, in several studies, 'low' concentrations of nitrogen (often nitrate or nitrate-nitrite) differed significantly – i.e., from < 1 to 5-7 µM – making it difficult to estimate this lower limit in relation to ambient natural concentrations in Tasmanian waters.

This review aimed to identify individual biophysical constraints to inform geospatial modelling. However, interactions do occur and modelling these relationships will be important to estimate optimal conditions for marine-based seaweed aquaculture. For example, enriched waters (i.e., relatively higher nutrient concentration) may dampen the effect of warmer waters in influencing growth and photosynthesis for *Undaria pinnatifida* and *Macrocystis pyrifera* (Fernández et al. 2020, Gao et al. 2012).

Table 4. Summary of biophysical characteristics uncovered via a literature review, expert opinion and analysis of occurrence data. For temperature, unless otherwise specified, this indicates *in-situ* temperature. Openness (this study): mean; range (10-80th percentile); number of sites. PAR: Photosynthetically Available Radiation (400-700 nm). Shaded in red indicates taxa sensitive to temperature.

Taxon	Temperature	Exposure and currents	Nutrient availability	Light availability
Asparagopsis armata	Lethal limits: 5 – 27 °C[1] Sufficient growth:10-20 °C[1] Maximum photosynthetic rate: 15-24 °C[2] Modelled maximum suitability: 15.5-18.5 °C[3] (*Asparogopsis* spp.) High tolerance to temperature (distribution in tropical to temperate waters)[15]	Sheltered to moderate[7] (*Asparogopsis* spp.) Grows in sheltered systems[15] Openness (this study): 0.07; 0.01-0.16; 74 sites	Preferred nitrogen form: Ammonium (ammonium concentration: 5-200 μM)[16]	General decline in photosynthetic rate with irradiances above 150 μmol photons m^{-2} s^{-1} [(2)]
Caulerpa brownii		Sheltered to moderate[7] Openness (this study): 0.13; 0.01-0.19; 173 sites		
Caulerpa geminata		Wave exposure (max acceleration)[8]: 0-0.67 m·s^{-2} Currents (min-max; annual average)[8]: 0 – 0.09 m·s^{-1} Sheltered[7] Openness (this study): 0.08; 0.003-0.16; 92 sites		
Chaetomorpha billardierii		Sheltered[7] Openness (this study): 0.07; 0.005-0.11; 21 sites		
Chaetomorpha coliformis		Sheltered[7] Openness (this study): 0.05; 0.005-0.09; 63 sites		
Cladophora vagabunda		Openness (this study): 0.001; 1 site		
Codium fragile	Maximum growth: 15-23°C[4]	*Codium fragile*: Sheltered to moderate[7] Openness (this study): 0.07; 0.005-0.13; 67 sites		Optimal conditions for photosynthesis: 900-1100 foot-candles (translates to 180-220 μmol photons m^{-2} s^{-1})[4] Growth experiment: 30 μmol photons m^{-2} s^{-1} for 12h light-period (equivalent to 1.3 mol photons m^{-2} d^{-1})[12]
Codium harveyi		Sheltered to moderate[7] Openness (this study): 0.06; 0.005-0.14; 34 sites		

Durvillaea potatorum	(*Durvillaea* spp.) Low temperature tolerance (restricted to southeast Australia)[17]	Exposed[7] (*Durvillaea* spp.) Grows in exposed environments[15] Openness (this study): 0.22; 0.04-0.36; 145 sites		
Ecklonia radiata	Thermal tolerance (experimental range): 5-25°C (salinity > 24 S_A); 5°C (salinity 6-18 S_A)[5] Considered a 'warm-temperate' species Moderate temperature tolerance (subtropical to temperate distribution)[15] No sporophytes developing above 22°C[17]	Mixed: sheltered to exposed[7] Grows in moderately exposed environments[15] Openness (this study): 0.17; 0.008-0.32; 505 sites	Nitrate (minimum for observed growth): 0.5 μM[17]	
Grateloupia turuturu		Sheltered to moderate[7] Openness (this study): 0.04; 0.006-0.09; 5 sites		
Lessonia corrugata	Critical thermal limit: ~22°C[7] Sensitivity: above ~20°C for weeks[7] Low temperature tolerance (restricted to southeast Australia)[15] Thermal optima: 14.97-16.71°C (multiple response variables; tissue erosion peaked at 20-22°C)[18]	Moderate to exposed[7] Openness (this study): 0.17; 0.008-0.33; 167 sites		
Macrocystis pyrifera	Distribution typically not exceeding 20°C[6] Critical thermal limit (adult sporophyte): ~20°C[7] Sensitivity (adult sporophyte): above ~18°C for weeks[7] Low temperature tolerance (restricted to southeast Australia)[15]	Canopy cover more variable, canopy loss greater, duration of low canopy cover longer at moderate to exposed sites[9] Mixed: sheltered to exposed[7] Grows in moderately exposed environments[15] Openness (this study): 0.14; 0.007-0.29; 164 sites	Nitrate: >1 μM[11]	Saturation of photosynthesis in field experiments (juvenile sporophytes): 2-3 mol photons $m^{-2} d^{-1}$ (Minimum for growth: 0.4-0.7 mol photons $m^{-2} d^{-1}$)[(13)]
Ulva lactuca var. lacinulata		*Ulva spp.*: Sheltered to moderate[7] Openness (this study): 0.09; 0.006-0.16; 95 sites		

Undaria pinnatifida	Thermal tolerance (experimental range; Day 10) of 5-25°C (salinity > 18 S_A); 5-20°C (salinity 6-33 S_A) [5] Optimal values for net photosynthesis rate (irradiance: 500 µmol photons m^{-2} s^{-1} for 12h:12h light-dark cycle): 16-20°C[14] Potentially wide temperature tolerance (but distribution limited in Australia)[15]	Mixed: sheltered to exposed[10] Sheltered to moderate[7] Grows in low to moderately exposed environments[15] Openness (this study): 0.03; 0.005-0.05; 36 sites		Compensation PAR: 2.1-5.9 µmol photons m^{-2} s^{-1} for 12h light-period (8-22°C); saturation PAR: 22.8-41.3 µmol photons m^{-2} s^{-1} for 12h light-period (8-22°C)[14]

1. Orfanidis 1991
2. Mata et al. 2006; Experimental
3. Casas et al. 2021
4. *Codium fragile*; New England; Fralick & Mathieson 1973; correlated with longer daylength during boreal summer
5. Experimental (adult sporophyte; New Zealand); Bollen et al. 2016
6. Cribb 1953
7. Expert opinion
8. Modelled hydrodynamics; July 2004 – July 2005; Port Philip Bay (Victoria); Crockett & Keough 2014
9. Field (California, USA); Graham et al. 1997
10. Field observations (New Zealand); Russell et al. 2008
11. Juvenile sporophytes; varies due to interaction with temperature (Zimmerman and Kremer 1984)
12. Ding et al. 2022; Experimental set-up (*Codium fragile*)
13. Dean and Jacobsen 1984, 1986; field experiments; southern California; when nutrients are sufficient
14. Sato et al. 2021; sporophytes; experimental; Japan
15. Visch et al. 2023; Based on expert opinion
16. Laboratory; 30 µmol photons m^{-2} s^{-1}; 20°C; Torres et al. 2021
17. Laboratory; samples from Tasmania; 17-42 µmol photons m^{-2} s^{-1}; 16h:8h Day:Night; Mabin et al. 2013
18. Laboratory; samples from Tasmania; James et al. 2024

SECTION 3: Preliminary spatial assessment of biophysical variables and data gaps

3.1 RATIONALE

Based on findings from previous sections, the aim of this section is to determine the spatio-temporal variability of biophysical constraints on seaweed aquaculture. This exercise is not meant to optimize siting because of its coarse resolution and lack of clear understanding of optimized growth conditions for several taxa. Instead, it is meant to guide further assessment at finer scales in areas of interest.

A coarse statewide assessment of relevant biophysical variables is presented; variables are directly mapped when available or proxies are used. It is important to note the focus is on coastal aquaculture; however, no explicit consideration has been made to restrict biophysical assessments to Tasmanian State waters. Instead, the purpose is to show coarse biophysical patterns, and in some cases, may extend offshore to demonstrate the general biophysical regime of select areas. Where relevant, data gaps are identified, and potential sources of data are identified to fill these data gaps in the future, particularly at a finer resolution in areas of interest.

This section also examines the potential for co-locating seaweed aquaculture with existing aquaculture in Tasmania, namely finfish aquaculture.

A synthesis of the distribution of seaweed taxa of interest and conditions of biophysical constraints is presented in Section 4.

3.2 METHODS

KEY FACTORS

Key biophysical variables influencing the siting of seaweed aquaculture are identified from previous sections. These include:

- **Temperature**: some seaweed taxa of interest are vulnerable to warm water temperature – e.g., *Macrocystis pyrifera, Lessonia corrugata*. A conservative approach examines mean and maximum observed temperature in an area (identifying waters > 20°C). Temperature varies spatially (along latitudinal gradient and under the influence of major ocean currents), and temporally (daily to seasonally).

- **Exposure**: Exposure relates to wave action and water movement. Optimal conditions for seaweed growth differ among taxa, i.e., sheltered to moderate to exposed environments. Exposure can vary spatially (e.g., geography of the coastline), and spatio-temporally (coastline and wind patterns). At a coarse scale, the assessment in this study examines the geography of the coastline (openness) as an indicator of suitability.

- **Light availability**: As primary producers, seaweed relies on light availability for growth. Light availability differs spatially (latitudinal gradient), and temporally, from diurnal patterns (day-night), to seasonal patterns. It is noted also that while studies have examined seaweed distribution *in-situ* on the seabed, seaweed aquaculture may occur closer to the surface (but not necessarily *at* the surface, i.e., the air-sea interface). Laboratory studies demonstrate the relationship between light availability and seaweed growth. Light penetration is influenced by reflection and refraction in the water column (turbidity) and varies spatiotemporally along coastlines due to terrestrial and marine sources of organic and inorganic load, re-suspension and mixing, and the presence of organisms, such as phytoplankton cells. In the context of this study, light availability at the surface – for example, Photosynthetically Available Radiation (PAR) – coupled with estimates of light attenuation in the water column can provide reasonable proxies of light conditions prior to infrastructure deployment (e.g., baseline conditions).

- **Coastal nutrient availability**: Nutrient availability is a key biophysical constraint limiting marine-based (coastal) seaweed aquaculture. Nutrients in the coastal zone can originate from terrestrial sources through coastal run-off and riverine discharge (catchment run-off), wastewater treatment, marine-based industrial activities (e.g., finfish aquaculture), and marine sources from upwelled nutrient-rich waters. In the context of this study, two pathways for nutrient availability are investigated:

    1) hydrography of Tasmania, namely the networks of rivers embedded in water catchments and coupled with population density and land use. Hydrography can also further be used to investigate spatio-temporal patterns in **salinity**, an important biophysical constraint not directly investigated in this study;
    2) Presence of finfish aquaculture as a source of nutrients (excess nitrogen) to seaweed aquaculture.

A preliminary biophysical assessment of suitable conditions for the cultivation of the seaweed taxa of interest is presented here. The assessment uses data, when available, at the scale of Tasmania; higher-resolution data may exist, and it is recommended a targeted biophysical assessment at a higher resolution be conducted in areas of interest.

Importantly, the assessment does not explicitly consider interactions among biophysical constraints. For example, while proximity to river discharge may enhance nutrient availability, it also increases turbidity which may limit light availability. Similarly, high nutrient availability can curb sensitivity to warmer waters in some taxa (Fernández et al. 2020).

DATA SOURCES

Temperature at the sea surface (sea surface temperature; SST) was based on satellite observations available on the Australian Ocean Data Portal hosted by the Integrated Marine Observing System (IMOS; imos.org.au). For this analysis, the dataset used was a Level 3S day-night, 'foundation' SST values derived from multiple sensors and averaged over a 72-hour period. Daily means are gridded at ~0.02° x 0.02° and represent the average of the highest quality values of SST over the 72-hour period. Values were adjusted for Sensor Specific Error Statistics (SSES) bias as recommended by the Group for High Resolution Sea Surface Temperature (GHRSST; values are available in the data files). Data were obtained for the period of 1 January 2014 to 31 December 2023. 'Foundation' data aim to represent ambient temperature at a depth of ~10m to account for the variability in the diurnal warm layer. Foundation SST is derived from skin SST by rejecting observations with low wind speed during the day and night, therefore removing grid cells that could have been impacted by diurnal warming.

Exposure data was estimated with geographic openness (methods are provided in Section 2). Openness was estimated at individual points 50 m off the coastline and equally spaced at 2-km intervals (n = 3296 estimates of openness around Tasmania).

Light availability in waters around Tasmania was estimated with available data on surface irradiance photosynthetically available radiation (PAR; 400-700 nm) and average attenuation coefficient of irradiance in the euphotic zone (i.e., surface to depth where ~1% of surface irradiance remains). Average attenuation coefficients (K_{PAR}; m^{-1}) estimated from satellite data were provided by Gattuso et al. (2020) as global monthly climatologies. This dataset processed satellite data from several platforms from 1998 to 2018 at a resolution of 1/24°. Gattuso et al. (2020) provides both PAR at the surface and at the bottom (in mol photons m^{-2} d^{-1}) and K_{PAR}. This value is integrated from sunrise to sunset. Average attenuation coefficients are modelled from average chlorophyll *a* concentration derived from satellite ocean colour in 'Case 1 waters' where phytoplankton is hypothesized to be the main contributor to light attenuation. However, attenuation coefficients in 'Case 2 waters' where turbidity is due to factors other than phytoplankton concentration cannot be as generally modelled as in 'Case 1 waters'. Instead, the presence of 'Case 2 waters' is analytically inferred using water reflectance at 555 nm; grid cells identified as 'Case 2 waters' are removed from data products. Empirical observations are needed in such cases.

Here, monthly climatologies of surface PAR and K_{PAR} are used to *estimate* irradiance (PAR) at 3m depth (i.e., PAR_{3m}) throughout the year. Areas where the seabed depth is less than 3m were removed. Seabed depth was derived from the AusBathyTopo 250m (Australia) 2023 Grid (resolution: 0.0025°; data available from Geoscience Australia at portal.ga.gov.au). This is meant to illustrate the spatiotemporal variability of light availability at a given depth (or the seabed) around Tasmania; acquiring data at a higher temporal and spatial resolution is recommended in specific areas of interest, and a vertical profile of irradiance can be derived for each grid cell if needed. PAR_z is computed as followed (based on Gattuso et al. 2020):

$$PAR_z = \exp\left(-K_{PAR} \times z\right) \times PAR_{surface}$$

where z = depth (3 m below the surface).

Because of the coarse temporal resolution, these data should be considered estimates only. Gattuso et al. (2020) provides estimates of PAR irradiance at the bottom. Using these data, it is inferred a slight bias occurs, i.e., the estimates from monthly climatology (rather than daily) may slightly overestimate irradiance.

Coastal nutrient availability is not currently adequately described in Tasmania at an appropriate resolution relevant to support a state-wide assessment for the siting of marine-based seaweed aquaculture. Tasmanian waters are generally considered oligotrophic (Hurd et al. 2023). Below are estimates of coastal and shelf nutrient concentration:

- Mercury Passage (nitrate): ~**0.80 µM** maximum values observed at the surface and bottom (Winter 2020); overall time period surveyed: August 2017-2021; values in µM are *converted* from available values provided in mg/L using the molecular weight of nitrate; EPA Tasmania (2021)
- Okehampton Bay (Mercury Passage; nitrates): mean **2.5 ± 1.3 µM** (**max: 5.1 µM**); March-November 2020; Visch et al. (2024)
- Maria Island National Reference Station: maximum values of **~5 µM** (surface; 0-10 m) and **~10 µM** (bottom; > 50m), with annual averages at the surface ranging from **~0.5-2.0 µM**. Peak concentration at the surface (~0-30m) in winter; peak concentration at depth (below ~30m) in summer; Butler et al. (2020b)

- Port Arthur (Tasman Peninsula; nitrate): ~**0.32-0.57 μM** (maximum values observed at the surface and bottom (May and March 2022, respectively); overall time period surveyed: October 2021 – May 2022; values in μM are *converted* from available values provided in mg/L using the molecular weight of nitrate; Environment Protection Authority (2022)
- Great Taylor Bay (southeast; south D'Entrecasteaux Channel): mean **2.3 ± 1.2 μM** (**max: 5.8 μM**); March-November 2020; Visch et al. (2024)
- Tower Bay (southeast; south D'Entrecasteaux Channel): mean **2.3 ± 1.0 μM** (**max: 4.1 μM**); March-November 2020; Visch et al. (2024)
- Derwent Estuary (southeast): close to 0 (in summer) to **1-1.45 μM** (in winter, lower values at the mouth of the Derwent); bottom water measurements January 2010 to April 2020; estimated from NO_X μg L^{-1} with nitrate molecular weight; Raes et al. (2022)

Nutrient availability in the coastal zone can originate from terrestrial and marine sources, either through natural processes or from anthropogenic activities and at times stressors. In Australia, coastal waters are typically 'low in nutrients' but availability is enhanced at times due to anthropogenic nutrient pollution (Clarke et al. 2021). Among other sources, river discharge is a key mechanism of input of nutrients into the coastal zone, and nutrient load in rivers is influenced by natural processes (e.g., precipitation, weathering) and anthropogenic factors (e.g., land use affecting run-off, industrial activities, wastewater treatment).

Tasmanian coastal waters are naturally influenced by two major sub-tropical ocean currents – the East Australian Current and the Zeehan Current – mixing with sub-Antarctic water, and their interaction with river discharge (Cresswell 2000, Cherukuru et al. 2014). Sources of anthropogenic nutrient loading include urban and rural run-off, point discharges from (terrestrial) industry, wastewater treatment plants and organic loading from finfish aquaculture (Clarke et al. 2021).

In the context of this study, information is provided about potentially relevant proxies of coastal nutrient availability. The focus is predominantly on terrestrial sources, although qualitative descriptions of the influence of major oceanic processes around the state are included in the synthesis (Section 4). Spatial information on potential terrestrial sources is meant to provide a coarse overview of the hydrology of Tasmania. It is necessary to investigate further in specific regions, as needed. **Hydrography** (rivers, minor rivers, and major rivers) is coupled with **population density** and **land use** over **catchment areas**, as well as the **presence of finfish aquaculture** as a marine-based source of nutrients.

SYNTHESIS

Information is synthesized by season where applicable (e.g., temperature, light availability). Monthly values are provided in Appendices 3 (temperature) and 4 (light availability).

3.3 RESULTS

TEMPERATURE

Seasonal patterns in maximum and average sea surface temperature between 1 January 2014 to 31 December 2023 are shown in Figure 4. Monthly patterns are provided in Appendix 3.

Maximum and average sea surface temperature is warmest in summer (December – February), with the warmest average recorded in waters near the Furneaux Group (16.3°C; Fig 4a). As expected, a clear latitudinal pattern in temperature is apparent, with coolest temperatures observed in the southeast (average of 14.1 °C in summer, Fig. 4a). The coldest maximum temperatures were observed in the D'Entrecasteaux Channel, northern Storm Bay, the Derwent Estuary, and Frederick-Henry Bay/Norfolk Bay in winter. Cooler temperatures are observed in winter and spring (Fig. 4c, 4d).

Observed maximum temperatures above 20°C over the 10-year period occurred in summer from the western side of Storm Bay in the southeast to the northwest of Tasmania, including the Furneaux Group (Fig. 4a). Maximum temperatures above 20°C were also observed in autumn, albeit over a more restricted spatial extent than in summer, most of which largely confined to the northernmost part of the east coast, the north coast and the Furneaux Group (Fig. 4b).

EXPOSURE

Spatial patterns of openness as a proxy for exposure are presented in Figure 5.

Relatively small values of openness – i.e., sheltered environments – are computed in sheltered bays, estuaries and along complex coastlines (Fig. 5). The southeast region had overall the smallest mean value of openness (0.05; Fig. 6), with semi-enclosed waters and bays in the north of the D'Entrecasteaux Channel, the Derwent Estuary, and Norfolk Bay. Intermediate values of openness in the southeast are located in the southern D'Entrecasteaux Channel, Storm Bay, and exposed lower Derwent Estuary. Other areas with a significant proportion of coastline (40-60%) in sheltered environments occur in the mid-east coast, the north coast (Tamar Estuary and Robins Passage), and the south coast (Port Davey). Macquarie Harbour is a large relatively sheltered environment in the otherwise highly exposed west coast.

Intermediate values of openness were common along the north coast, mid-east coast and Furneaux Group (Fig. 5).

High values of openness - i.e., 'exposed' environments – were determined along the west coast off the Tasman Peninsula, and the north east coast (Fig. 5). Exposed environments are also common on the south coast and southern tip of Bruny Island in the southeast. Highest mean value of openness was calculated off the Tasman Peninsula (0.24; Fig. 6) with second highest being King Island (0.23; Fig 6).

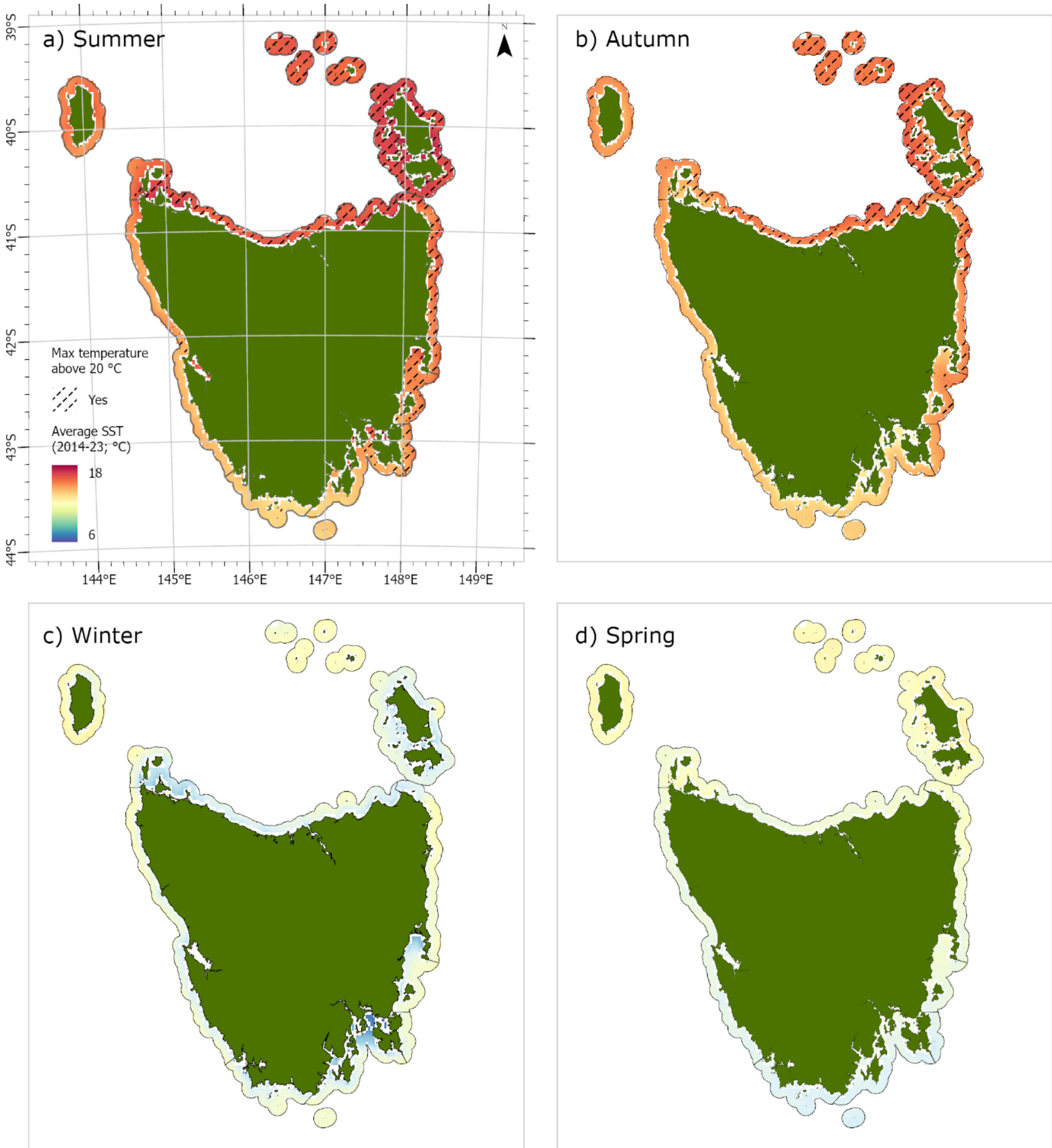


Figure 4. Maximum sea surface temperature (SST; 'foundation' temperature obtained via satellite) within 10 km of the coast of Tasmania from 1 January 2014 to 31 December 2023. Hashed lines indicate areas where maximum temperature is greater than 20°C. Also shown are mean temperatures within nine areas (see Figure 2). (a) Summer: December – February; (b) Autumn: March – May; (c) Winter: June – August; (d) Spring (September – November).

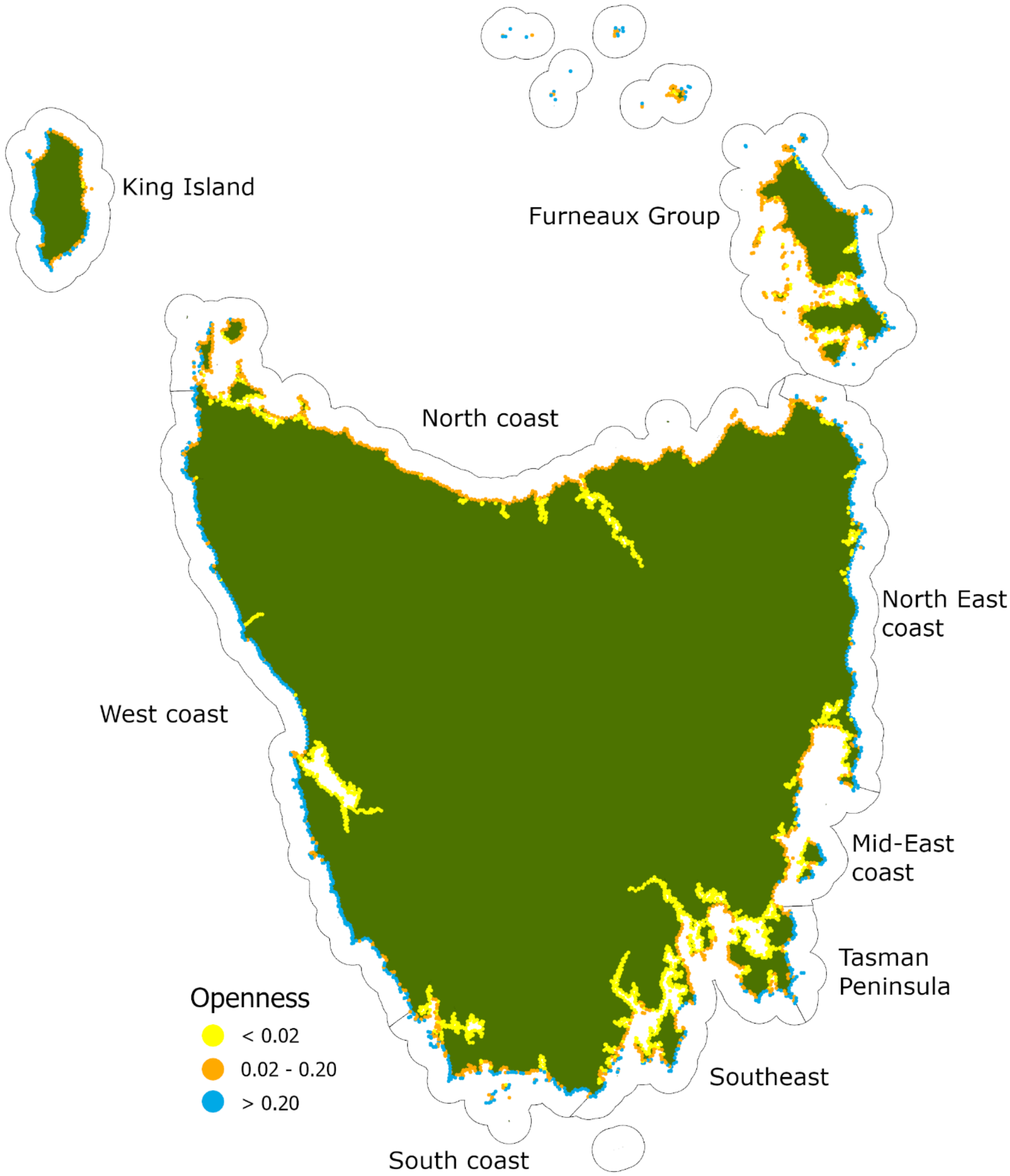


Figure 5. Openness index calculated 50m off the coast at 2-km intervals around Tasmania.

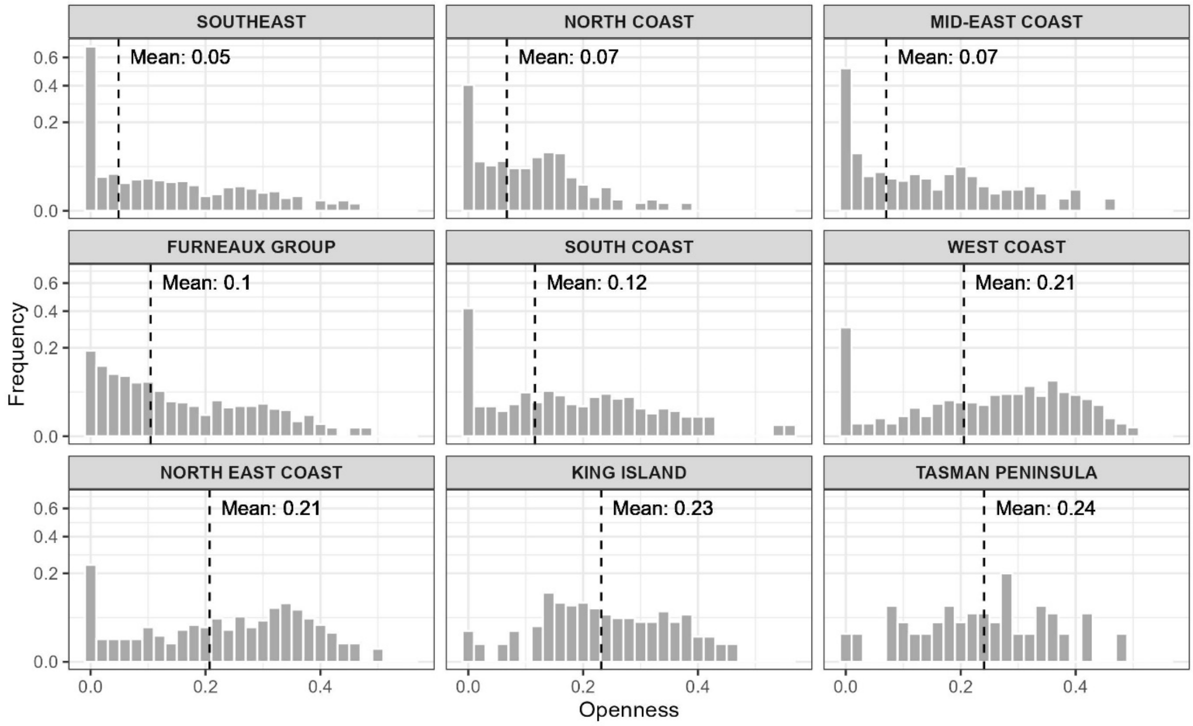


Figure 6. Relative frequency of openness measured 50m off the coast at 2-km intervals in nine areas around Tasmania (see Figure 5).

LIGHT AVAILABILITY

Seasonal patterns in average photosynthetically available radiation (PAR) estimated at 3m below the surface from monthly climatologies of PAR and K_{PAR} (1998-2018; Gattuso et al. 2020) are provided in Figure 7. Monthly patterns are provided in Appendix 4.

As expected, higher average PAR is observed in summer, with highest irradiance expected along the north coast, the Furneaux Group and King Island (Fig. 7a). Second-highest averages are observed in spring (Fig. 7d). Winter displays the lowest irradiance (Fig. 7c).

Lower irradiance is observed in all seasons in some nearshore areas, particularly the southeast region in the Derwent Estuary and D'Entrecasteaux Channel. It is hypothesized 'Case 2 waters' – where the main factor influencing light attenuation is *not* phytoplankton – are present in this region, more so in winter (Fig. 7c) but also in autumn and spring in the northern part of the D'Entrecasteaux Channel (Fig.7b,d). 'Case 2 waters' also seem to occur along the south coast, and throughout the year in Macquarie Harbour.

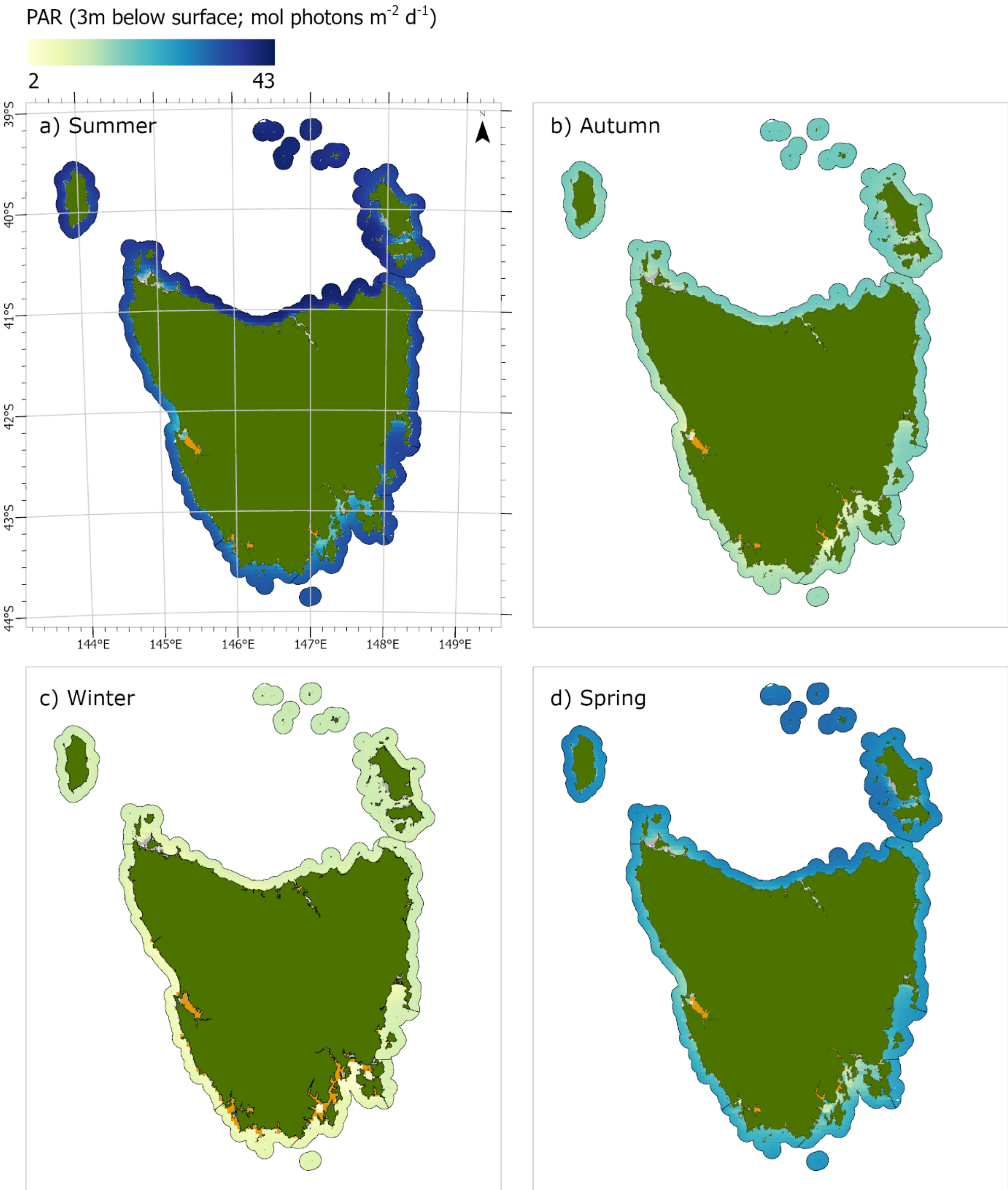


Figure 7. Photosynthetically Active Radiation (PAR; mol photons m^{-2} d^{-1}) estimated at 3m below the surface based on monthly climatology (1998-2018) of surface PAR and average attenuation coefficients K_{PAR} (m^{-1}) using datasets provided by Gattuso et al. (2020). Shown in grey are areas where seabed depth < 3m; shown in orange is inferred 'Case 2 waters'. (a) Summer: December – February; (b) Autumn: March – May; (c) Winter: June – August; (d) Spring (September – November).

Coastal Nutrient Availability

Hydrography is used in the context of this study as a proxy to highlight potential for coastal nutrient availability. Major rivers, rivers, and minor rivers are shown in relation to water catchment areas in Tasmania in Figure 8. Population density is shown in Figure 9, while land use is shown in Figure 10.

Major rivers in Tasmania include the River Derwent and Huon River (discharge in southeast area), the Gordon/Franklin Rivers (discharge in west coast area – Macquarie Harbour), Arthur River (discharge into northern west coast), and the South Esk River, fed by the Macquarie and Meander Rivers (discharge into north coast – Tamar Estuary). Along the north coast, other major rivers include River Forth and Mersey River flowing to Leith and Devonport, respectively. On the eastern side of the north coast, major rivers include the Great Forester River and Ringarooma River.

Major rivers do not discharge into the east coast, but several smaller rivers connect to the coast in this region (e.g., Meredith River, Prosser River, Scamander-Douglas River). Similarly, no major rivers discharge into the south coast and southern west coast. There are no major rivers on King Island and the Furneaux Group, and off the eastern coast of the Tasman Peninsula.

Population density is concentrated in the Hobart region in the southeast, and Launceston, at the head of the Tamar Estuary. Other smaller urban centres are located along the north coast (Fig. 9). A similar pattern is observed for intensive land uses (Fig. 10).

Agricultural land use is closely co-located with the networks or major rivers and rivers. Much of it is concentrated south of Launceston in the midlands, and connected to the Tamar Estuary via the South Esk, Macquarie and Meander Rivers. The joint Clyde River and River Derwent north of Hobart, along with catchments of the Jordan and Coal Rivers, also host (largely dryland) agriculture. Irrigated agriculture and plantation are common along the northwest coast.

Existing finfish aquaculture can be a source of nutrients for seaweeds. Most of Tasmania's finfish aquaculture marine leases (primarily for Atlantic Salmon) are located in the southeast region. Some marine farming leases are currently licensed for both finfish and selected seaweed species (*Macrocystis pyrifera, Lessonia corrugata,* and *Ecklonia radiata*) in the southern D'Entrecasteaux Channel, Northwest Bay, Crooked Billet Bay and Port Arthur. One additional lease is licensed in Mercury Passage (with the addition of *Ulva lactuca* as seaweed).

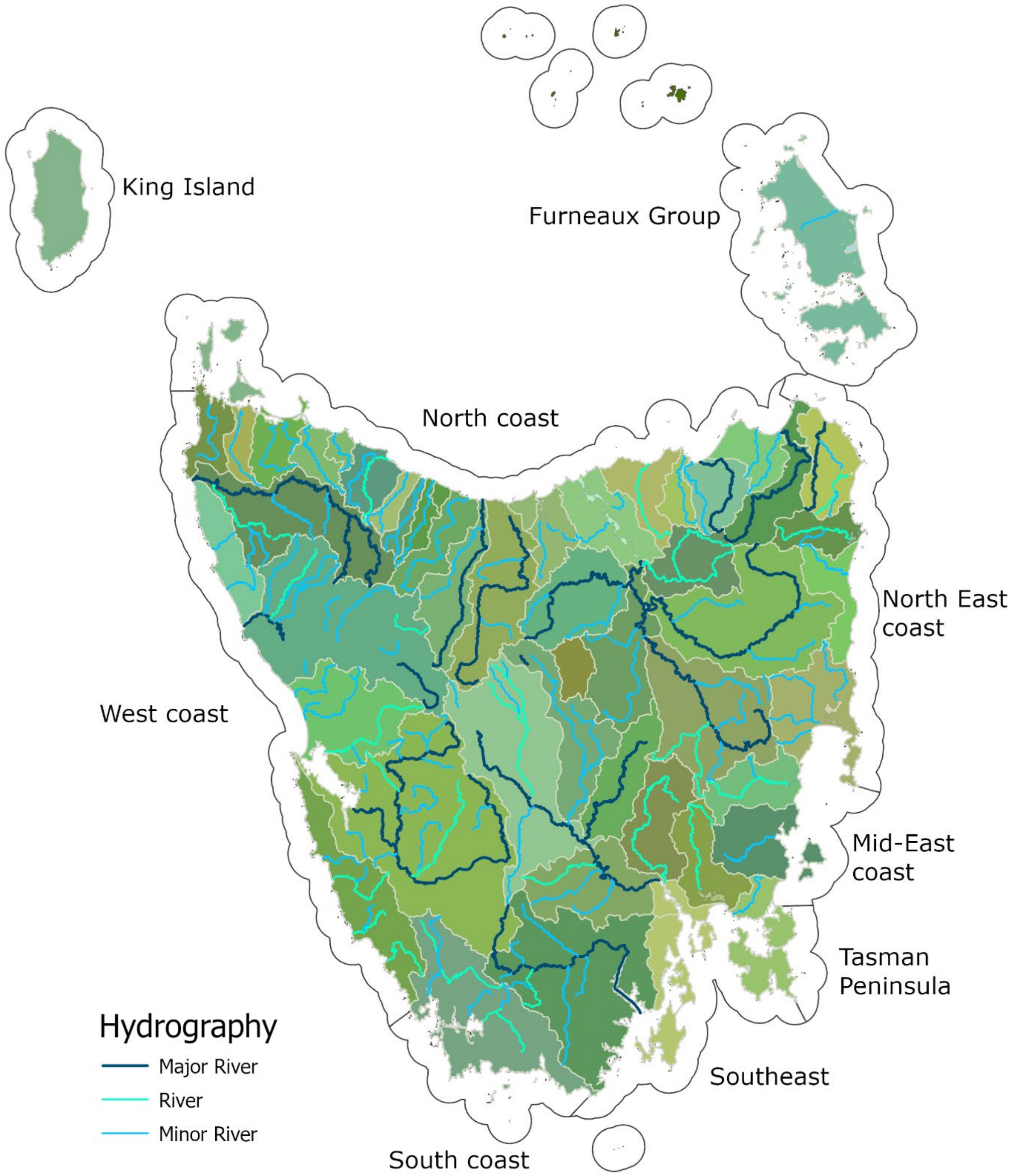


Figure 8. Hydrography of Tasmania (major rivers, rivers, and minor rivers) and water management regions (hydrogeological catchment areas).

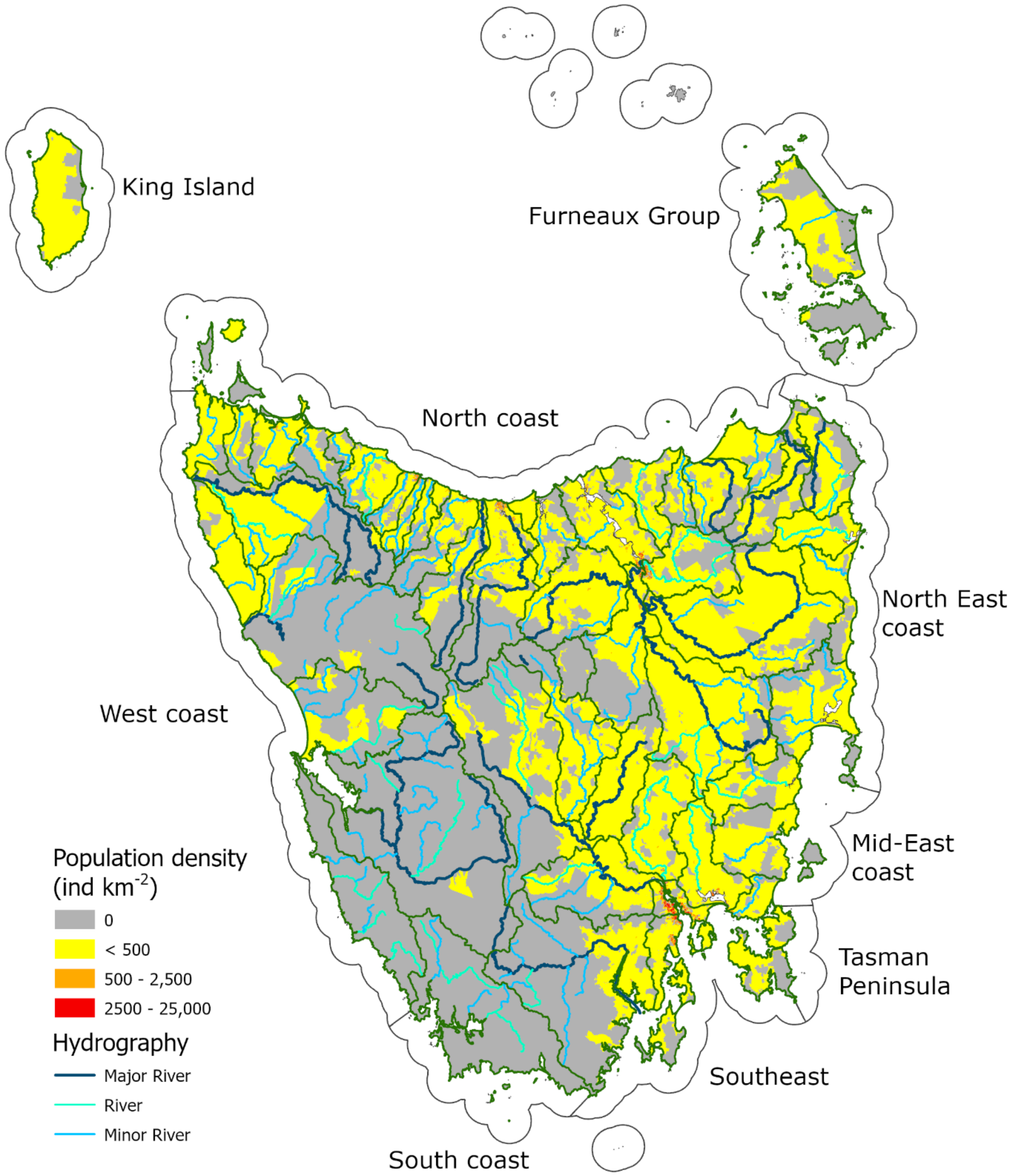


Figure 9. Population density (Australian Bureau of Statistics, 2021) in Tasmania shown with hydrography (major rivers, rivers, minor rivers). Boundaries of catchment area are shown in dark green.

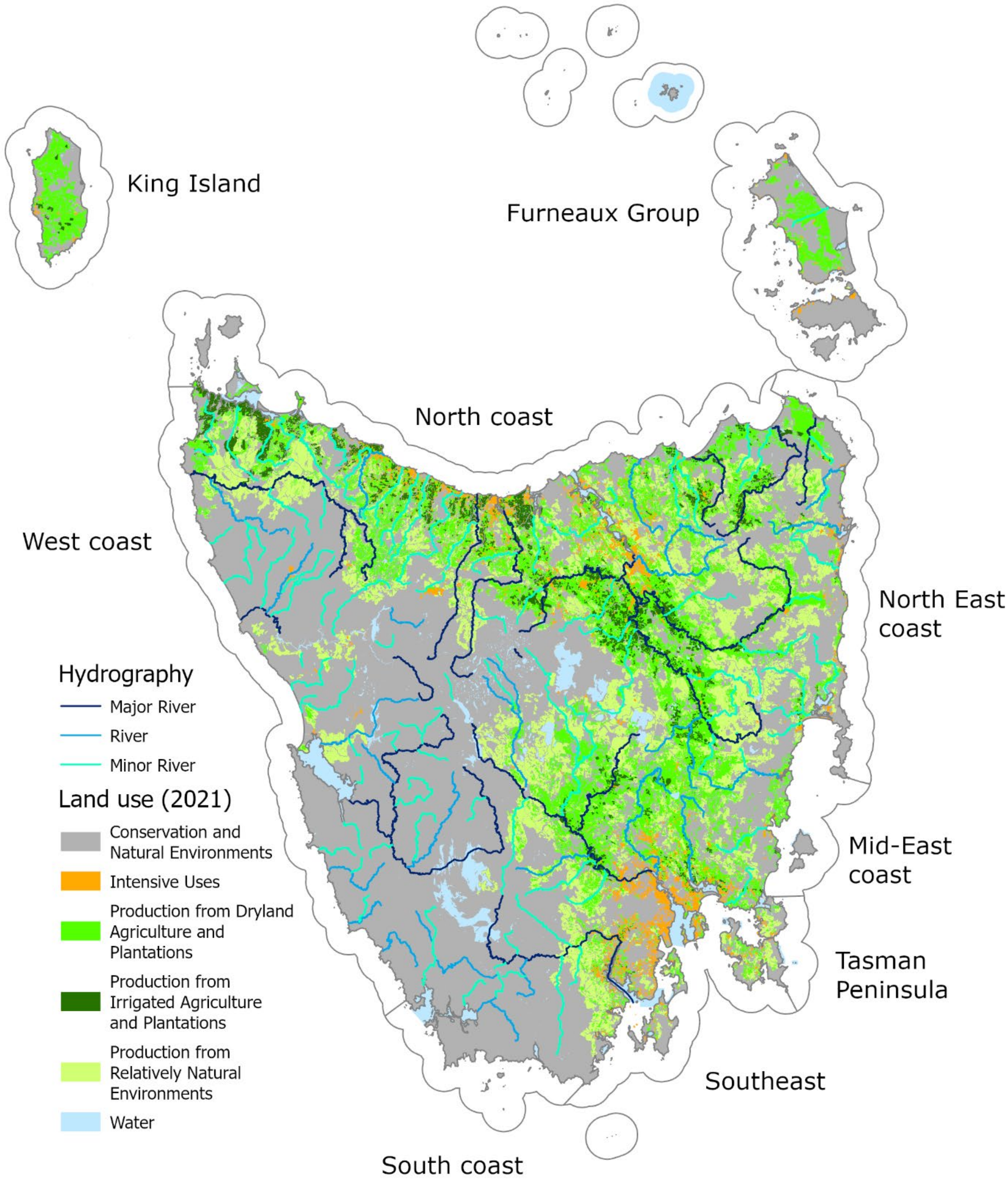


Figure 10. Land use (2021) in Tasmania shown with hydrography (major rivers, rivers, minor rivers). Also shown are boundaries of water management regions (catchment areas).

FILLING DATA GAPS

Clear data gaps remain to fully understand biophysical constraints and optimal conditions for the siting of aquaculture for seaweed taxa of interest. In addition to resolving optimal biophysical conditions – through laboratory or field experiments – gaps remain to systematically assess these conditions in Tasmania. Critically, biophysical variables employed in this study are coarsely spatially resolved and/or proxies of underlying key biogeochemical processes (e.g., hydrography and influence of oceanic currents for coastal nutrient availability). A key step forward is to enhance spatiotemporal resolution of data in areas of interest. Avenues to fill these gaps – and particularly at a finer spatiotemporal scale – are detailed below.

1) **In-situ samples for assessment and ground-validation**:
    - Temperature (vertical profile and time series)
    - Light availability

2) **Monitoring for sporadic but consequential events**:
    - Precipitation and flooding events
    - Marine heat waves

3) **Exposure: Wind patterns in areas of interest**
    - Detailed time series either from wind/wave models or wind stations

4) **Light availability and coastal nutrient availability: High-resolution time series of turbidity and primary production**
   In areas of interest, it is recommended the approach employed be complemented with higher-resolution satellite imagery, and potentially refined to estimate irradiance at a depth of interest. Imagery collected with the Multispectral Instrument (MSI) aboard satellites Sentinel-2A and Sentinel-2B (European Space Agency) could be a valuable source of information in areas of interest to infer turbidity, and hence light availability at depth of interest over the growing period. Data are available at a high-resolution (10, 20, 60 m) as a cohesive Analysis Ready Data package as standardised surface reflectance data from Digital Earth Australia (knowledge.dea.ga.gov).

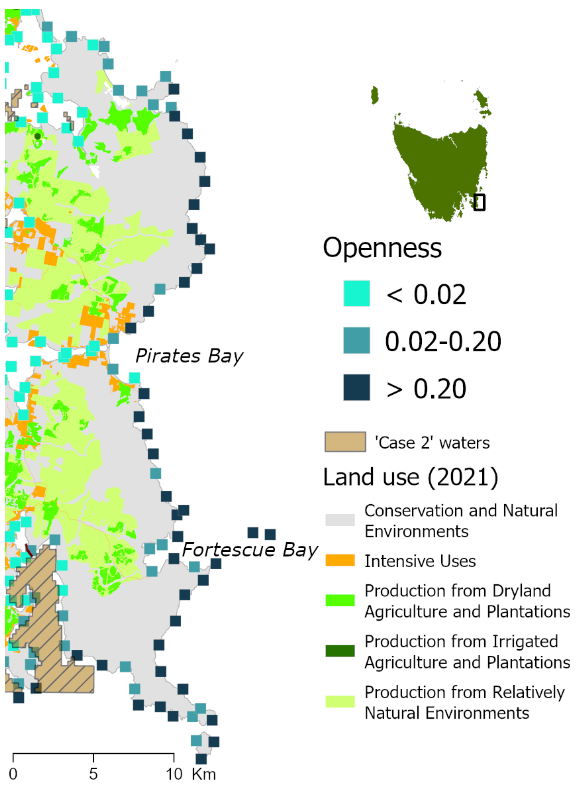
SECTION 4: Spatial synthesis of distribution and biophysical conditions

This section provides a synthesis of occurrence data (from Section 1) and a preliminary biophysical assessment (Sections 2 and 3) in nine geographic areas around Tasmania.

The information provided includes:

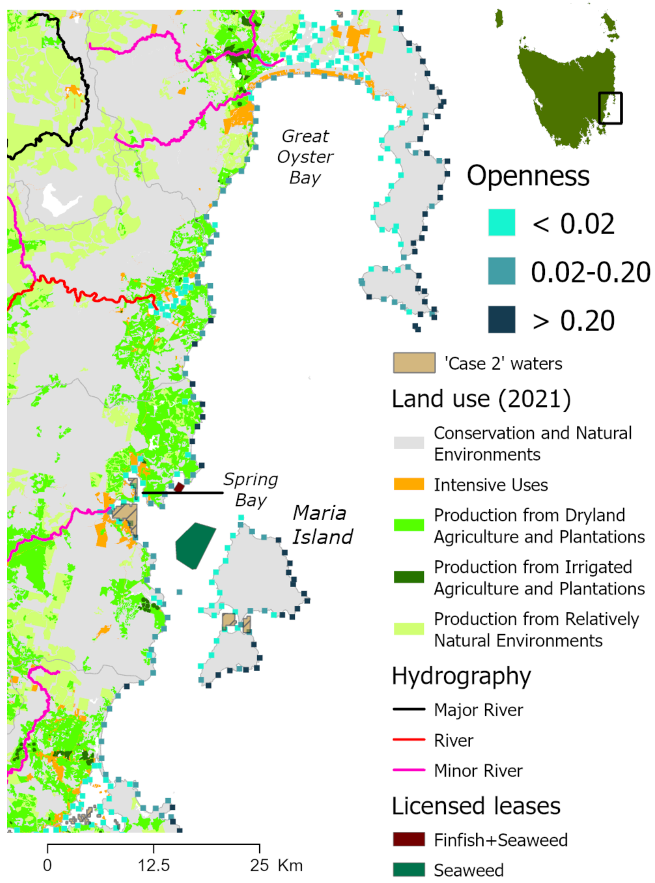
- Observed seaweed taxa of interest (and number of sites at which they have been observed).
- Descriptive statistics on water temperature derived from sea surface temperature (detailed in Section 3): annual range (average by month) and whether maximum temperature above 20°C have been observed
- Qualitative description of exposure based on spatial variability of (quantitative) openness indices
- Spatial variability in light availability at 3m below the surface and descriptive statistics: annual range (average by month) and if and where 'Case 2 waters' have been observed at any time during the year
- A qualitative assessment of hydrography (rivers connecting to the coast), coastal land use and summary of coastal population density to support further research on spatio-temporal variability of coastal nutrient availability (from terrestrial sources). This also includes where available information on the influence of oceanic currents.
- Marine farming leases currently licensed for finfish only, finfish and seaweed, oysters and seaweed, and seaweed only.

TASMAN PENINSULA



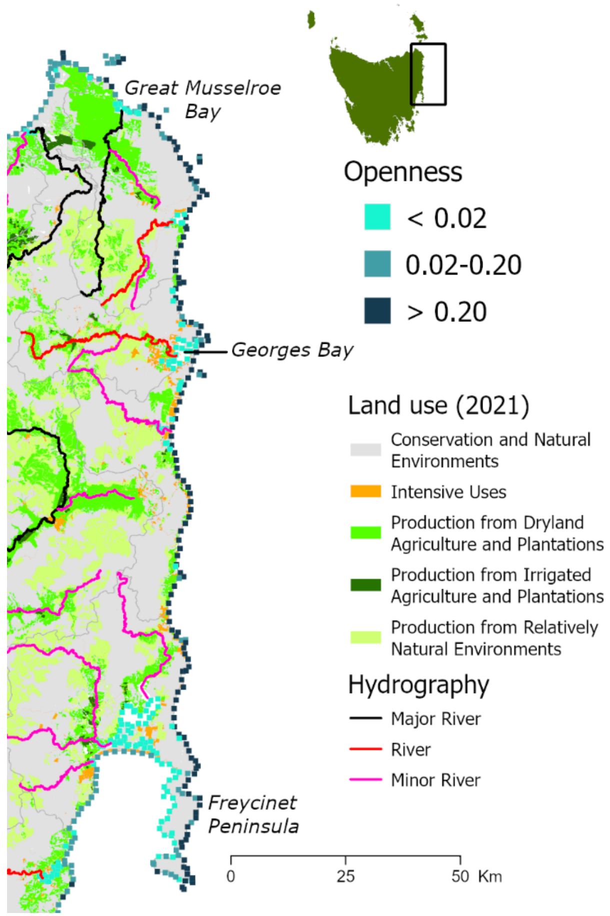
SEAWEED OCCURRENCE	*Caulerpa brownii* (3), *Caulerpa geminata* (1), *Durvillaea potatorum* (20), *Ecklonia radiata* (43), *Lessonia corrugata* (15), *Macrocystis pyrifera* (14), *Ulva spp.*(9)
WATER TEMPERATURE (WITHIN 10 KM OF COASTLINE)	Average (annual range, by month): 10.4 (September) – 15.8 (March) °C Waters above 20°C have been observed in summer throughout the area.
EXPOSURE	Mostly exposed (openness > 0.20; mean: 0.24; highest among areas) with intermediate values in Fortescue and Pirates Bays
LIGHT AVAILABILITY (WITHIN 10 KM OF COASTLINE)	Light availability at 3m below the surface oscillates around state average with no significant spatial variability. This is consistent across all seasons. Average (annual range, by month): 7.4 (June) – 35.7 (January) mol photons m^{-2} d^{-1} No 'Case 2 waters' observed along the east coast of the Tasman Peninsula (Gattuso et al. 2020)
COASTAL NUTRIENT AVAILABILITY	No (major, minor) river connecting to the coast. Coastal land use dominated by conserved and natural environments, with the exception of Pirates Bay (intensive uses) and Fortescue Bay (production in relatively natural environment and from dryland agriculture/plantation).

Mid-East Coast



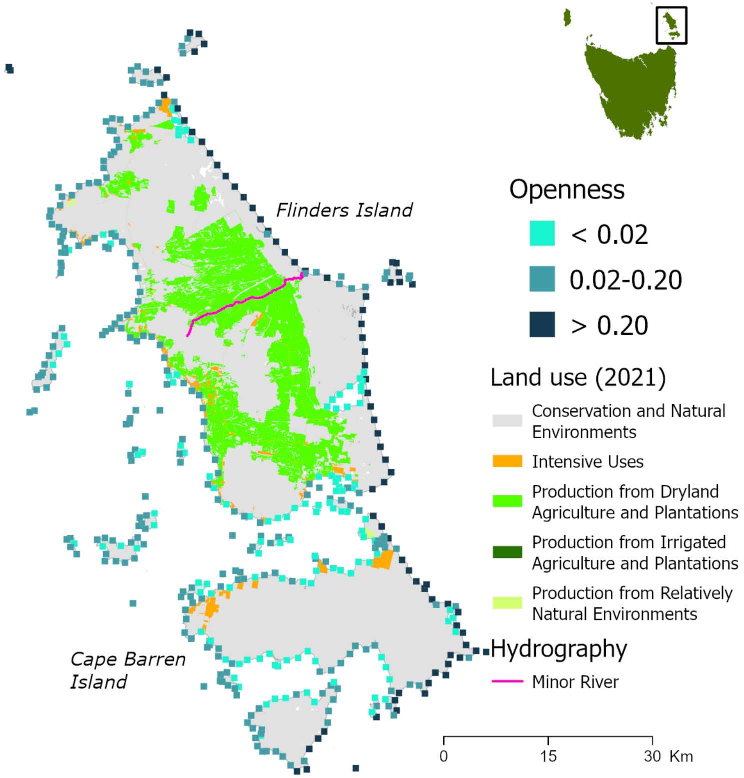
Seaweed occurrence	*Asparagopsis armata* (20) *Caulerpa brownii* (26) *Caulerpa geminata* (16) *Chaetomorpha billardierii* (9) *Chaetomorpha coliformis* (11) *Codium fragile* (23) *Codium harveyi* (13) *Durvillaea potatorum* (5) *Ecklonia radiata* (61) *Grateloupia turuturu* (1) *Lessonia corrugata* (9) *Macrocystis pyrifera* (3) *Ulva spp.* (25) *Undaria pinnatifida* (18)
Water temperature	Average (annual range, by month): 10.4 (August) – 16.0 (February) °C Waters above 20°C have been observed in summer throughout the area, and sporadically in autumn (east of Maria Island, Great Oyster Bay).
Exposure	Mixed openness (proxy of exposure) with exposed area seaward of Maria Island, and intermediate openness for most of the coastline. Sheltered areas are found in protected bays (e.g., Spring Bay and Moulting Lagoon north of Great Oyster Bay).
Light availability	Light availability at 3m below the surface oscillates around state average year-round. Spatial variability occurs in summer and spring, with slightly less light penetration in the northern portion of Great Oyster Bay and in Mercury Passage. Average (annual range, by month): 7.3 (June) – 35.9 (January) mol photons m^{-2} d^{-1} Sporadic 'Case 2 waters' in Blackman Bay (year-round), Spring Bay/Prosser Bay (winter, spring), Shoal Bay/Riedle Bay (winter) and Moulting Lagoon (autumn/winter)
Coastal nutrient availability	Three rivers flowing directly in the coast (2 minor, 1 river): into Prosser Bay/Spring Bay and Great Oyster Bay. Mainly influenced by the East Australian Current (nutrient-poor); East Coast in general less impacted by river discharge due to lack of major rivers (Cherukuru et al. 2014). One finfish aquaculture lease (also for seaweed) and one seaweed aquaculture lease in Mercury Passage. Coastal land use dominated by production from dryland agriculture and plantation north of Spring Bay. Sporadic intensive uses around Great Oyster Bay. Conservation and natural environments common (including Maria Island).

North East Coast



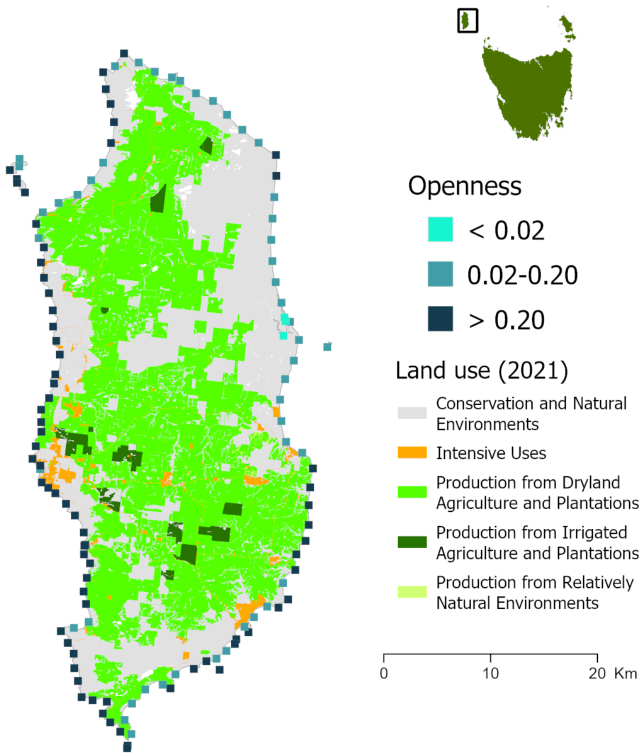
Seaweed occurrence	*Asparagopsis armata* (2) *Caulerpa brownii* (8) *Caulerpa geminata* (1) *Chaetomorpha billardierii* (3) *Chaetomorpha coliformis* (3) *Codium fragile* (3) *Durvillaea potatorum* (26) *Ecklonia radiata* (97) *Lessonia corrugata* (26) *Macrocystis pyrifera* (12) *Ulva spp.* (12)
Water Temperature	Average (annual range, by month): 10.9 (August) – 16.4 (February) °C Waters above 20°C have been observed in summer, and sporadically in autumn (off Freycinet Peninsula and northern portion of coast).
Exposure	Mostly exposed with some more sheltered areas (e.g., Georges Bay). Mean openness: 0.21.
Light availability	Light availability at 3m below the surface is near state average in summer and spring, with relatively more light penetration than elsewhere in the state in autumn and winter. Weak spatial variability occurs in summer, with slightly less light penetration in Georges Bay. Average (annual range, by month): 8.4 (June) – 36.4 (December) mol photons $m^{-2}\ d^{-1}$ Highly sporadic 'Case 2 waters' in Georges Bay (winter; not shown on map)
Coastal nutrient availability	Four rivers flowing into the coast, including one major river (Great Musselroe River) flowing into Great Musselroe Bay. No major river flowing into the northeast coast facing the Tasman Sea (where influence is dominated by the East Australia Current) Mainly influenced by the East Australian Current (nutrient-poor); East Coast in general less impacted by river discharge due to lack of major rivers (Cherukuru et al. 2014). Coastal land use: Sporadic intensive uses and production from dryland agriculture and plantation. Conservation and natural environments are common.

Furneaux Group



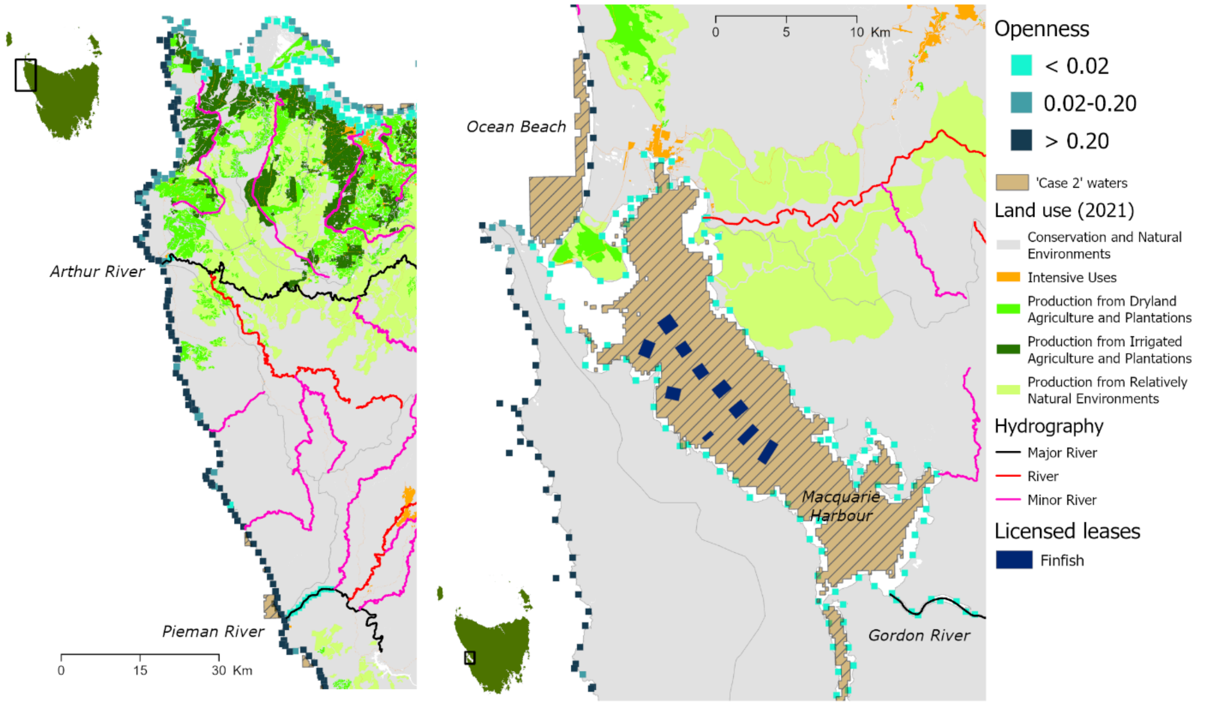
Seaweed occurrence	*Asparagopsis armata* (16) *Caulerpa brownii* (45) *Caulerpa geminata* (7) *Codium fragile* (4) *Codium harveyi* (4) *Durvillaea potatorum* (1) *Ecklonia radiata* (48) *Macrocystis pyrifera* (4) *Ulva spp.* (1)
Water temperature	Average (annual range, by month): 10.5 (August) – 17.3 (February) °C Waters above 20°C have been observed in summer and autumn throughout the area.
Exposure	Mixed exposure: exposed on the eastern coast, intermediate on the western coast. Sheltered areas between Cape Barren Island and Flinders Island. Mean openness: 0.10.
Light availability	Light availability at 3m below the surface is consistently higher than state average, particularly in spring and summer. Spatial variability is higher in summer and spring with weaker light penetration in Franklin Sound between Cape Barren Island and Flinders Island. Average (annual range, by month): 8.8 (June) – 40.1 (December) mol photons m^{-2} d^{-1} Extremely sporadic, spatially restricted 'Case 2 waters'; no consistent patterns (not shown on the map)
Coastal nutrient availability	One (minor) river. Dominated by conservation and natural environments. Production from dryland agriculture and plantation on Flinders Island.

King Island



Seaweed occurrence	*Asparagopsis armata* (2) *Caulerpa brownii* (10) *Caulerpa geminata* (3) *Codium fragile* (3) *Durvillaea potatorum* (3) *Ecklonia radiata* (6) *Lessonia corrugata* (1) *Macrocystis pyrifera* (3) *Ulva spp.* (1)
Water Temperature	Average (annual range, by month): 11.3 (August) – 16.0 (March) °C Waters above 20°C have been observed highly sporadically in summer, and along the west coast in autumn.
Exposure	Intermediate to exposed coastline: exposed on the west and southeast coast, intermediate on the east coast. High mean openness: 0.23 (second highest among areas).
Light availability	Light availability at 3m below the surface is consistently higher than state average, particularly in spring and summer. No clear patterns in spatial variability (minimal). Average (annual range, by month): 8.5 (June) – 39.6 (December) mol photons m^{-2} d^{-1} No 'Case 2 waters' observed
Coastal nutrient availability	No (major, minor) rivers. Land dominated by production from dryland agriculture and plantations (sporadic irrigated production). Conservation and natural environments present in the northeast of the island. Sporadic intensive uses.

West coast



Seaweed occurrence	
Caulerpa brownii (6)	*Lessonia corrugata* (2)
Caulerpa geminata (2)	*Macrocystis pyrifera* (7)
Durvillaea potatorum (8)	*Ulva spp.* (1)
Ecklonia radiata (11)	

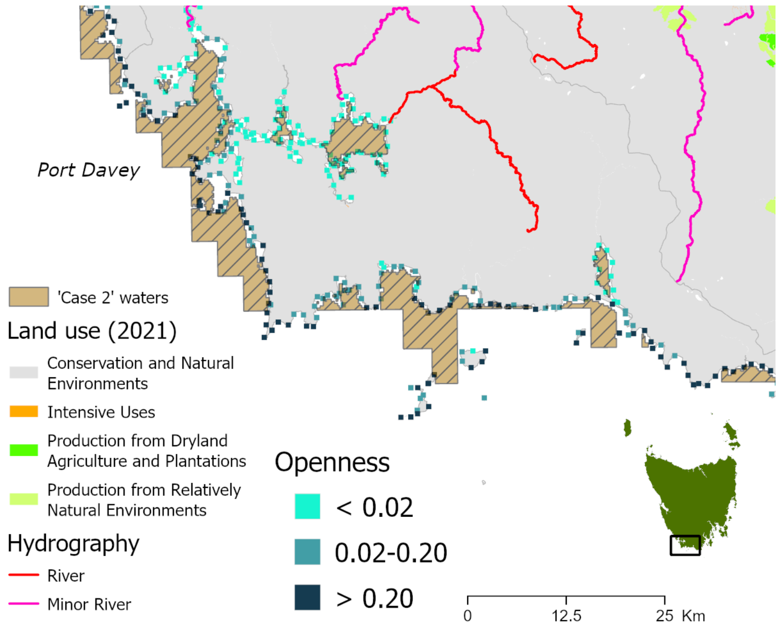
Water Temperature

Average (annual range, by month): 10.6 (September) – 15.2 (February) °C

Waters above 20°C have been observed in summer in Macquarie Harbour, and north of the entrance of the Harbour along Ocean Beach. Observed in ocean waters at the entrance of Macquarie Harbour in autumn.

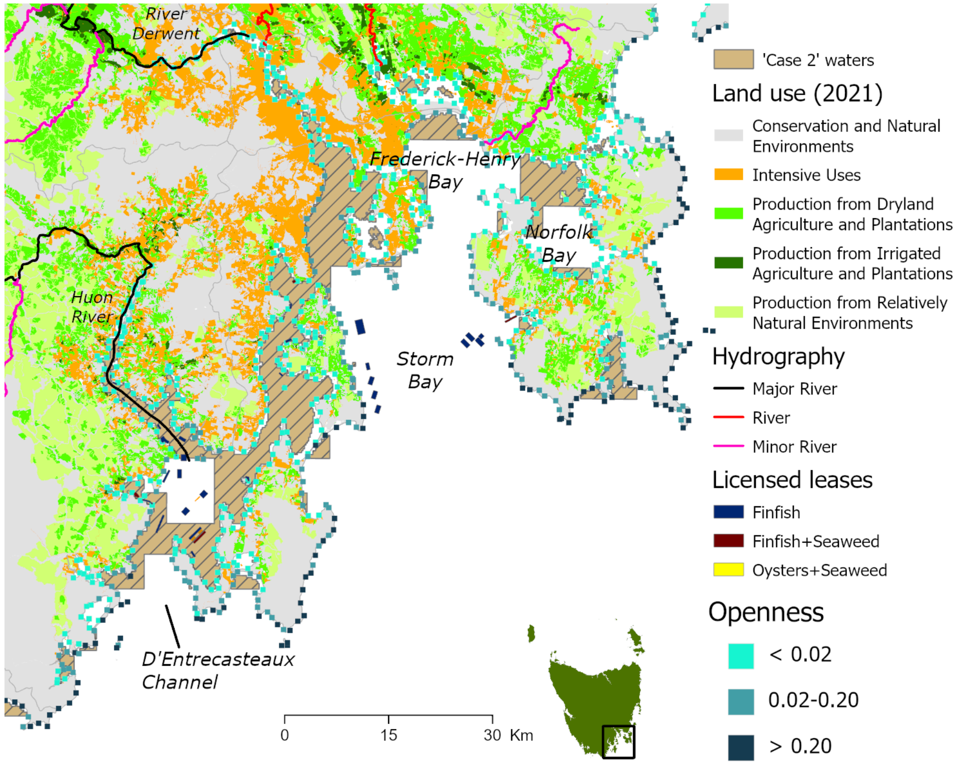
Exposure	Predominantly exposed on the northern west coast, with sporadic intermediate exposure along the southern west coast. Large sheltered environment in Macquarie Harbour. Mean openness: 0.21.
Light availability	Light availability at 3m below the surface is consistently less than state average, with high spatial variability in spring and summer. Relatively weaker light penetration is expected at the mouth of Macquarie Harbour and along the exposed coast north of the Kelly Channel (Ocean Beach). Average (annual range, by month): 5.8 (June) – 33.8 (December) mol photons m^{-2} d^{-1} Persistent, year-round 'Case 2 waters' in Macquarie Harbour; sporadic occurrence along the coast in winter; highly sporadic occurrence in autumn/spring
Coastal nutrient availability	14 rivers flowing into the coast, including three major rivers: Arthur, Pieman, and Gordon Rivers. Finfish aquaculture leases in Macquarie Harbour. Coastal land use dominated by conservation and natural environments, with the exception of the far northern tip where production occurs (both irrigated and dryland). Production from relatively natural environments is present on the northern shore of Macquarie Harbour.

South Coast



Seaweed occurrence	*Asparagopsis armata* (3) *Caulerpa brownii* (19) *Caulerpa geminata* (24) *Chaetomorpha billardierii* (1) *Chaetomorpha coliformis* (11) *Codium fragile* (5) *Codium harveyi* (1) *Durvillaea potatorum* (34) *Ecklonia radiata* (47) *Lessonia corrugata* (35) *Macrocystis pyrifera* (24) *Ulva spp.* (3)
Water temperature	Average (annual range, by month): 10.4 (September) – 14.3 (February) °C Waters above 20°C have been observed highly sporadically in summer, and not observed in autumn.
Exposure	Mixed exposure: sheltered environment in Port Davey and surroundings, intermediate to exposed coastline along the ocean coast.
Light availability	Light availability at 3m below the surface is consistently less than state average, with spatial variability in spring and summer (in the vicinity of Port Davey). Average (annual range, by month): 5.5 (June) – 33.6 (January) mol photons m^{-2} d^{-1} 'Case 2 waters' present year-long in parts of Port Davey, Payne Bay, and Bathurst Harbour; present along the whole coast in winter
Coastal nutrient availability	Three rivers flowing into the coast (Port Davey). River flow (discharge) is higher along the south relative to other areas. Influenced by river discharge and the Zeehan Current (nutrient-rich); high river flow (into Port Davey; Cherukuru et al. 2014) Coastal land use dominated by conservation and natural environments, there is no production.

SOUTHEAST



SEAWEED OCCURRENCE

Asparagopsis armata (21)
Caulerpa brownii (17)
Caulerpa geminata (23)
Chaetomorpha billardierii (7)
Chaetomorpha coliformis (38)
Cladophora vagabunda (1)
Codium fragile (23)
Codium harveyi (7)
Durvillaea potatorum (46)
Ecklonia radiata (152)
Grateloupia turuturu (4)
Lessonia corrugata (78)
Macrocystis pyrifera (82)
Ulva spp. (40)
Undaria pinnatifida (18)

WATER TEMPERATURE

Average (annual range, by month): 10.0 (August) – 15.0 (February) °C

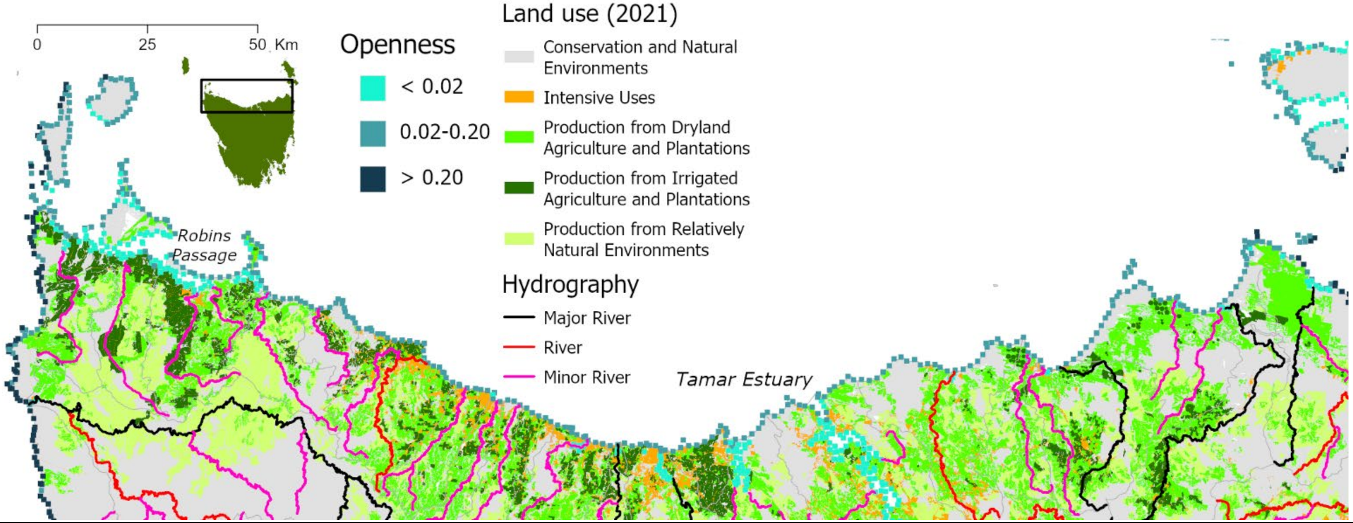
Waters above 20°C have been observed in summer in eastern Storm Bay, Frederick-Henry Bay/Norfolk Bay, south of the Tasman Peninsula, and sporadically in northern D'Entrecasteaux Channel. Observed highly sporadically in autumn in Norfolk Bay.

EXPOSURE

Dominated by sheltered environments in Huon River, D'Entrecasteaux Channel, Derwent Estuary, Norfolk Bay, and Port Arthur. Intermediate exposure (and sporadic exposed environments) in the southern D'Entrecasteaux Channel, east coast of Bruny Island, Storm Bay, and northern coast of Frederick-Henry Bay. Exposed environments found off South Bruny Island, and southern coast of Tasman Peninsula. Mean openness (0.05) lowest among areas, with > 60% of assessed coastline in relatively sheltered environments.

LIGHT AVAILABILITY	Light availability at 3m below the surface is consistently the least relative to state average, with highest spatial variability among all areas, particularly in spring and summer, but present year-long. Relatively stronger light attenuation observed in the D'Entrecasteaux Channel (mid to northern), Derwent Estuary, north of Storm Bay (more pronounced at the mouth of the Derwent Estuary), and in Frederick-Henry Bay/Norfolk Bay. Average (annual range, by month): 5.1 (June) – 31.8 (December) mol photons m^{-2} d^{-1} 'Case 2 waters': persistent, year-long in Huon River and River Derwent/upper Derwent Estuary, and Pitt Water. Common in north D'Entrecasteaux Channel and Port Esperance (autumn to spring). Widespread in winter: most of the D'Entrecasteaux Channel, Northwest Bay, Derwent Estuary, Norfolk Bay, north of Frederick-Henry Bay, and Port Arthur.
COASTAL NUTRIENT AVAILABILITY	Four rivers flowing into the coast, including two major rivers: Huon River and River Derwent. Complex and seasonal influence of the East Australian Current (nutrient-poor; summer), the Zeehan Current (nutrient-rich; winter), and sub-Antarctic water (nutrient-rich; winter); mixing with Huon and Derwent Rivers; high river flow (e.g., Huon River; Churukuru et al. 2014). Finfish aquaculture in D'Entrecasteaux Channel and Storm Bay Coastal land use dominated by intensive uses and high population density. Production from dryland and relatively natural environment off the southern D'Entrecasteaux Channel, north Bruny Island, the Tasman Peninsula and Sorell area. River Derwent catchment including areas of dense (dryland and irrigated) production in the midlands.

North Coast



Seaweed occurrence

Asparagopsis armata (10)
Caulerpa brownii (39)
Caulerpa geminata (15)
Chaetomorpha billardierii (1)
Codium fragile (6)
Codium harveyi (9)
Durvillaea potatorum (2)
Ecklonia radiata (40)
Lessonia corrugata (1)
Macrocystis pyrifera (15)
Ulva spp (3)

Water Temperature	Average (annual range, by month): 10.1 (August) – 17.1 (February) °C Waters above 20°C have been observed in summer and autumn throughout the area.
Exposure	Dominated by intermediate exposure, with the exception of sheltered environments in the Tamar Estuary and Robins Passage. Second lowest: sheltered environments around Robins Passage and Tamar, intermediate along the open coastline.
Light availability	Light availability at 3m below the surface is higher than state average in summer, autumn, and spring, but average in winter. High spatial variability in summer and spring, with higher light attenuation at the head of the Tamar and in Perkins Bay/Boullanger Bay in the northwest. Average (annual range, by month): 7.7 (June) – 39.4 (December) mol photons $m^{-2} d^{-1}$ Highly sporadic 'Case 2 waters' in the lower Tamar River/Estuary (autumn/winter; not shown in the map). Note: Tamar is only coarsely resolved in the dataset.
Coastal nutrient availability	22 rivers, including 4 major rivers (and the Tamar River/Estuary): River Forth, Mersey River, Great Forester River, Ringarooma River. Influenced by Bass Strait waters, East Australian Current (nutrient-poor) and river discharge; high river flow (e.g., Mersey River; Cherukuru et al. 2014) Coastal land use dominated by intensive uses and production (dryland, irrigated), particularly west of the Tamar Estuary.

Summary and recommendations

This study presents a preliminary assessment of the biophysical conditions and potential for selected seaweed taxa for aquaculture in Tasmania. This included providing details on:

- Contemporary distribution in Tasmanian coastal waters of 15 seaweed taxa of interest for sea-based cultivation;
- Ecological knowledge on constraints and limiting factors influencing the distribution of these taxa in natural environments (or tested in laboratory conditions) that could influence the siting of seaweed aquaculture in Tasmania;
- Available spatial information – largely from remote sensing data products – that could inform decision-making for seaweed aquaculture siting, and identifying avenues to fill data gaps, if needed;
- Relevant information for the siting of seaweed aquaculture synthesized in nine regions in Tasmania.

The synthesis of conditions by regions revealed contrasts and similarities:

- The **southeast of Tasmania** is a **seaweed-rich**, generally **cold**, **moderately exposed** environment with **extensive sheltered areas**, with probable **pulses of nutrient-rich waters** (in winter, from marine and terrestrial sources). However, the region is impacted by **high river discharge**, **high population density**, and **intensive land uses**, which may **sporadically reduce light availability**. **Finfish aquaculture** also occurs most commonly in the southeast, particularly in Storm Bay and the D'Entrecasteaux Channel.

- The **east coast** is **seaweed-rich**, **cool** region **vulnerable to sporadic warming**, **moderately exposed to exposed** region – particularly off the Tasman Peninsula and the northern east coast. Major rivers do not flow in the east coast, which likely makes **water generally clearer**, except for Georges Bay. Nutrient loading largely depends on oceanic sources.

- The **Furneaux Group** is a relatively **warmer region clearly vulnerable to sporadic warming**, particularly in summer and autumn, **moderately exposed coast facing Bass Strait**, and relatively **less dense land use**.

- The **north coast** is a relatively **warmer region clearly vulnerable to sporadic warming**, particularly in summer and autumn, **moderately exposed coast facing Bass Strait.** The region is **extensively dominated by dryland and irrigated production** along its coast and **several major rivers**, including the Tamar Estuary. **Intensive land use** occurs, particularly from the mouth of the Tamar Estuary to Burnie. Light availability may be impacted by river discharge, but likely concentrated at the mouth of the major rivers.

- King island is a **relatively cooler** environment despite its latitude, with **exposed environments for most of its coastline**, dryland and irrigation with restricted intensive land use.

- The **west and south coast** are **cooler**, **exposed** environments with **sporadic sheltered areas (e.g., Macquarie Harbour, Port Davey)**. **Several major rivers** flow in the west and south coast from the wet **protected and natural environments** dominating the coastal zone. **Poorly populated area**, with **light availability likely impacted by heavy river discharge in sheltered areas** (e.g., Gordon River flowing into Macquarie Harbour). Seaweed richness is under-sampled along the west coast. Macquarie Harbour hosts finfish aquaculture; however, 'Case 2 waters' are found throughout most of the harbour at least once during the year. This may limit light availability for seaweed cultivation.

RECOMMENDATIONS

This study is meant to provide a preliminary assessment of the biophysical conditions and potential for seaweed aquaculture in Tasmanian coastal waters, with consideration for co-location with existing aquaculture, such as finfish. Caveats remain to fully assess this potential, noting further steps may not need to be conducted at a state-wide scale. Three main recommendations to augment this present study are provided below:

1) Information on suitable environmental conditions for the cultivation of several seaweed taxa of interest was lacking. For some species, information was available in their natural habitat (albeit not always in Tasmania), while environmental requirements or niche for some taxa was lacking or could not be readily found for this study. Other taxa – such as *Undaria pinnatifida* – were better resolved because of overseas experience in cultivation. This is to be expected for emerging cultivated species in Tasmania. However, it is needed to **better resolve limiting and optimal environmental conditions for several of the seaweed taxa of interest**. Two additional considerations are added here:
    a. There is a need for a more detailed assessment of operational needs and requirements.
    b. It is suggested to focus on fewer taxa of interest. Fifteen taxa were considered which can dilute the effort to focus on key taxa for which opportunities are more obvious in the short-to-medium term.

2) This assessment was a coarse state-wide overview of biophysical constraints. In this context, data provided is coarse, since finer-scale data collation is time-consuming and may ultimately not be needed. It is therefore important to **identify priority areas of interest, and in these areas increase spatiotemporal resolution of key variables of interest:**
    - Temperature: *in-situ* monitoring particularly for sporadic events, such as marine heat waves if relevant
    - Exposure: augment openness data with high-resolution wind or wave data
    - Light and nutrient availability:
        - *In-situ* monitoring to uncover light and nutrient regime
        - Higher-resolution satellite data products in areas of interest
        - Further refine hydrographic analysis with precipitation, catchment use, and river flow discharge data

3) This assessment focused on biophysical environments only. A necessary step to fully understand potential is to couple biophysical information with socio-economic considerations and other ocean uses, including but not limited to the presence of finfish aquaculture.

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APPENDIX 1 – References (seaweed occurrence data from the literature)

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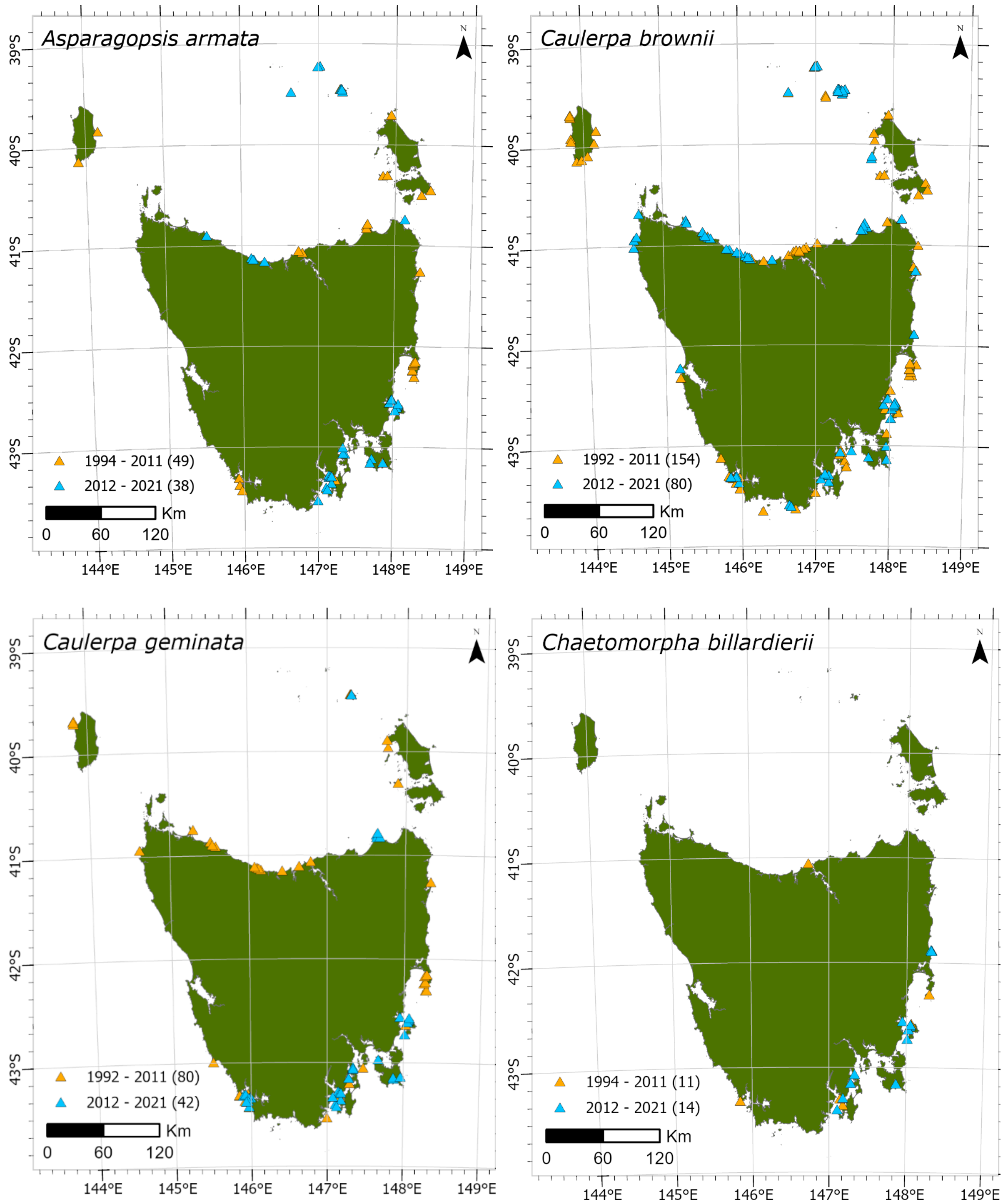
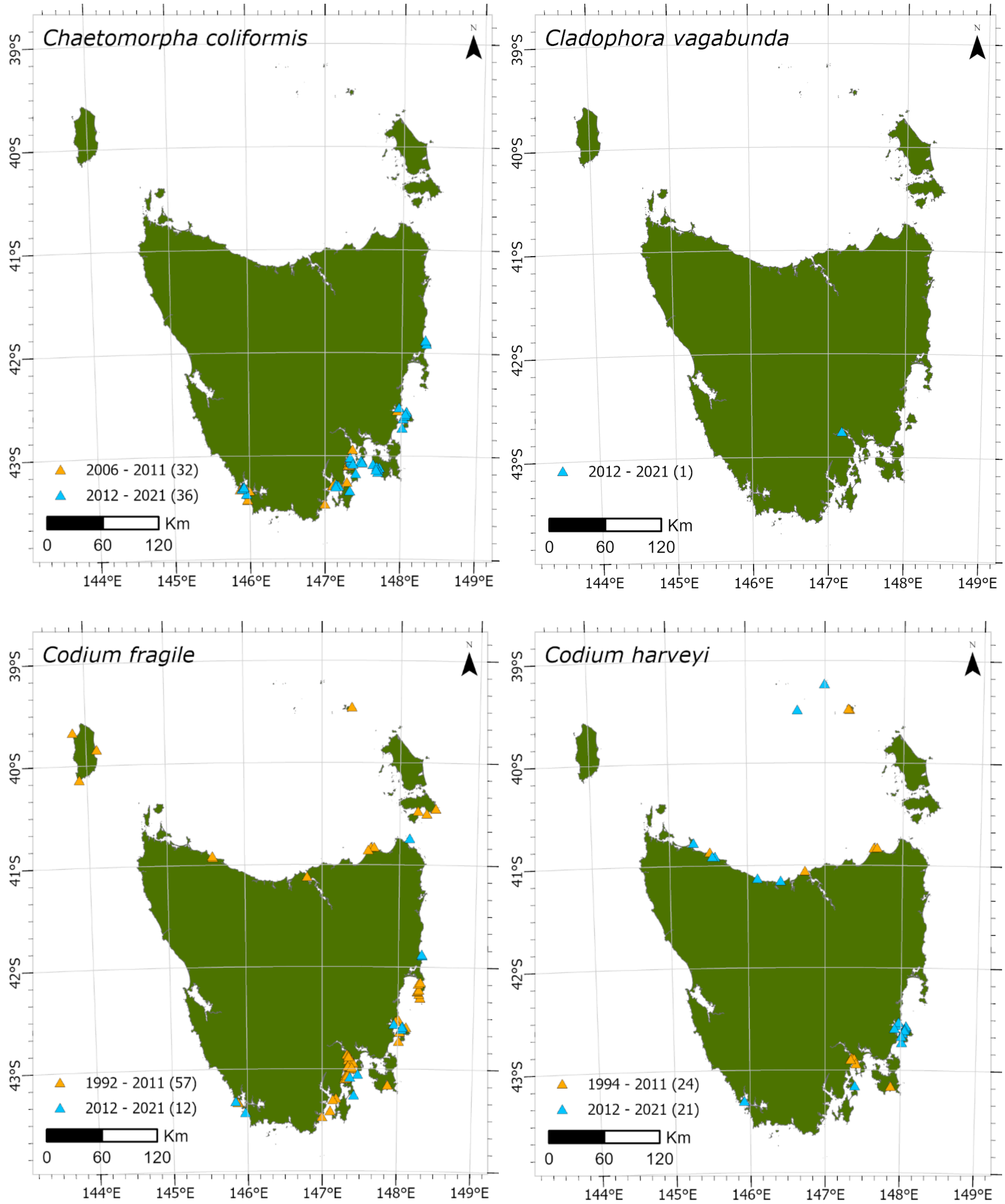
APPENDIX 2 – Distribution of seaweed taxa of interest in Tasmania

Data derived from 568 sites between 1984 and 2021. Data are segregated before and 2012 and number of sites where the taxon was observed is specified.



APPENDIX 2 (continued)



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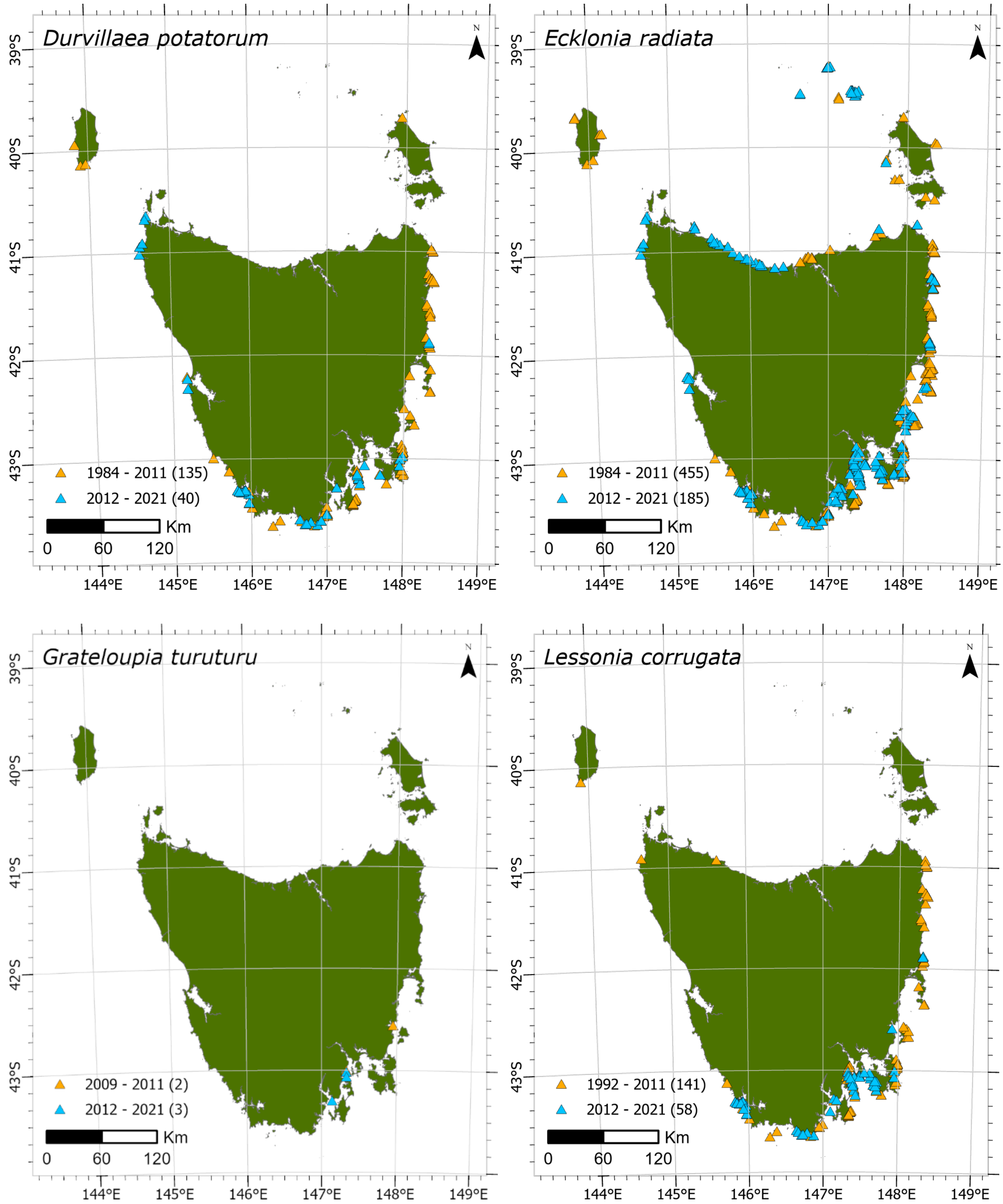

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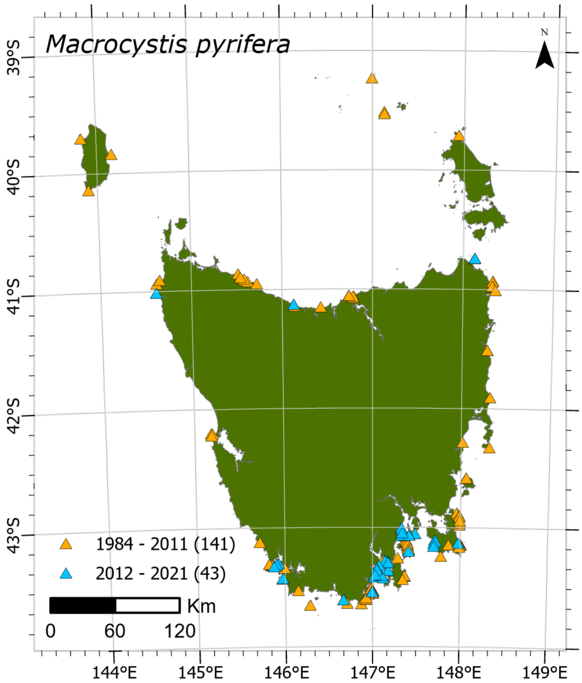
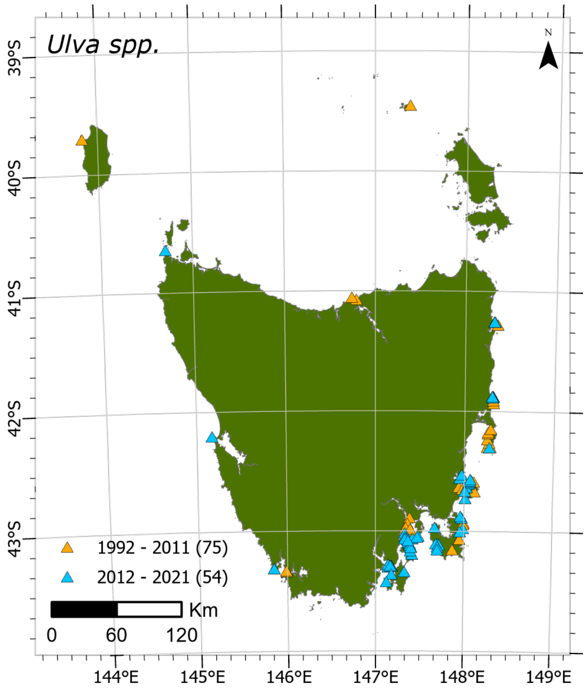
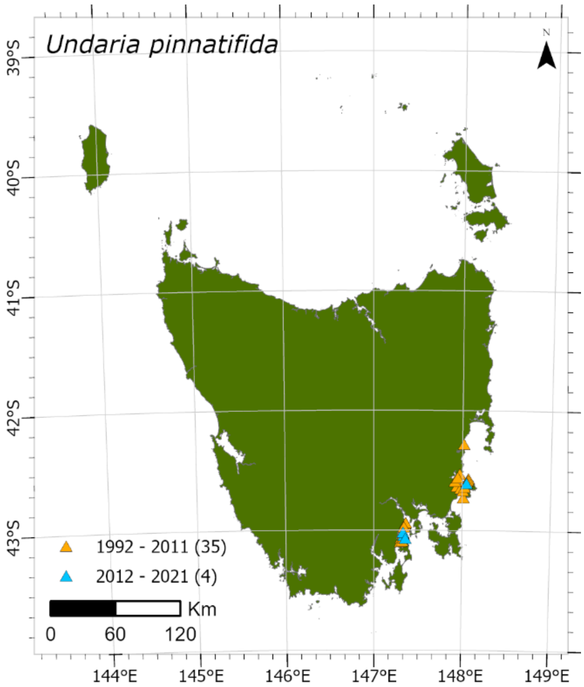
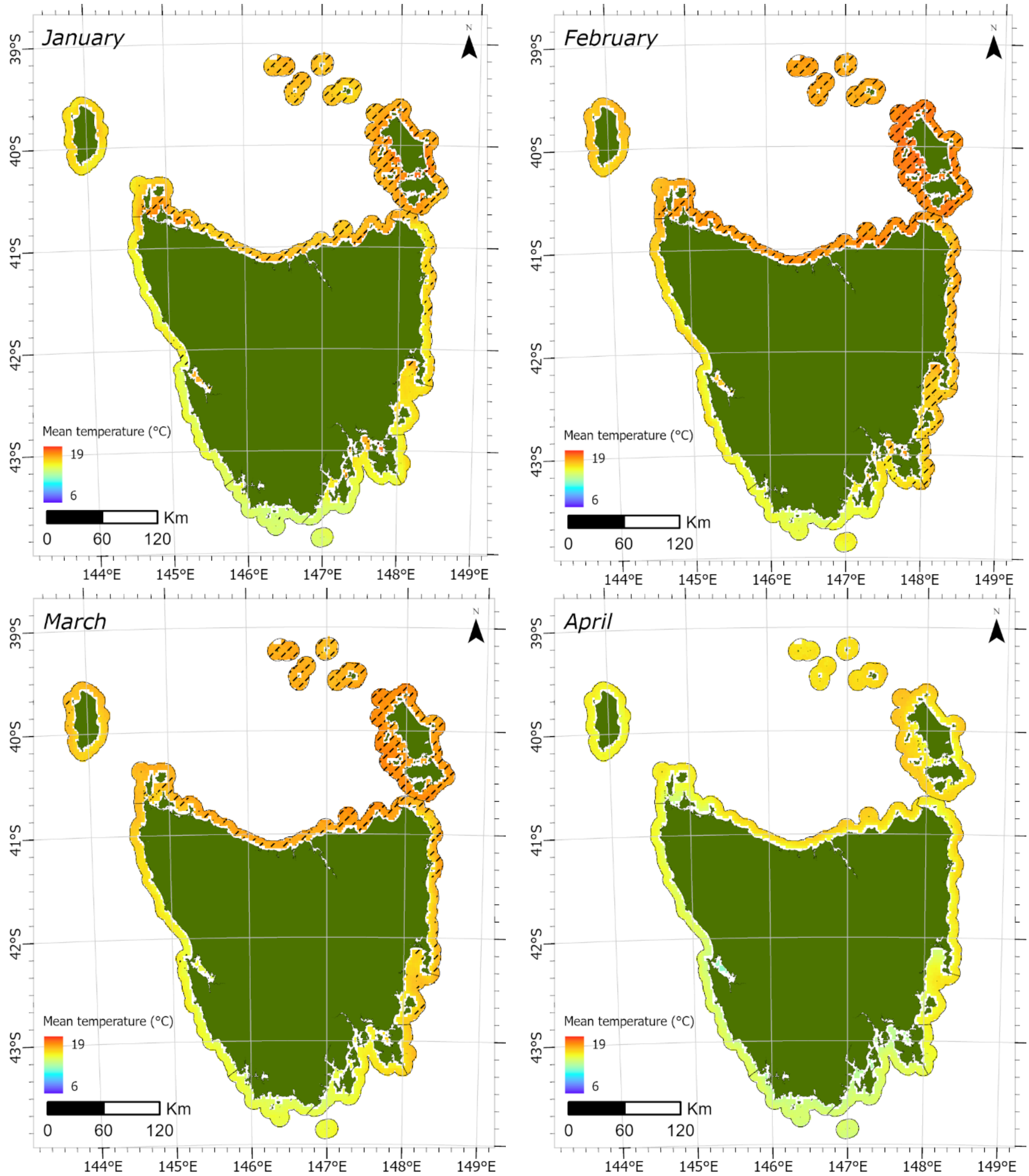






APPENDIX 3 – Monthly sea surface temperature in Tasmania (2014-23)



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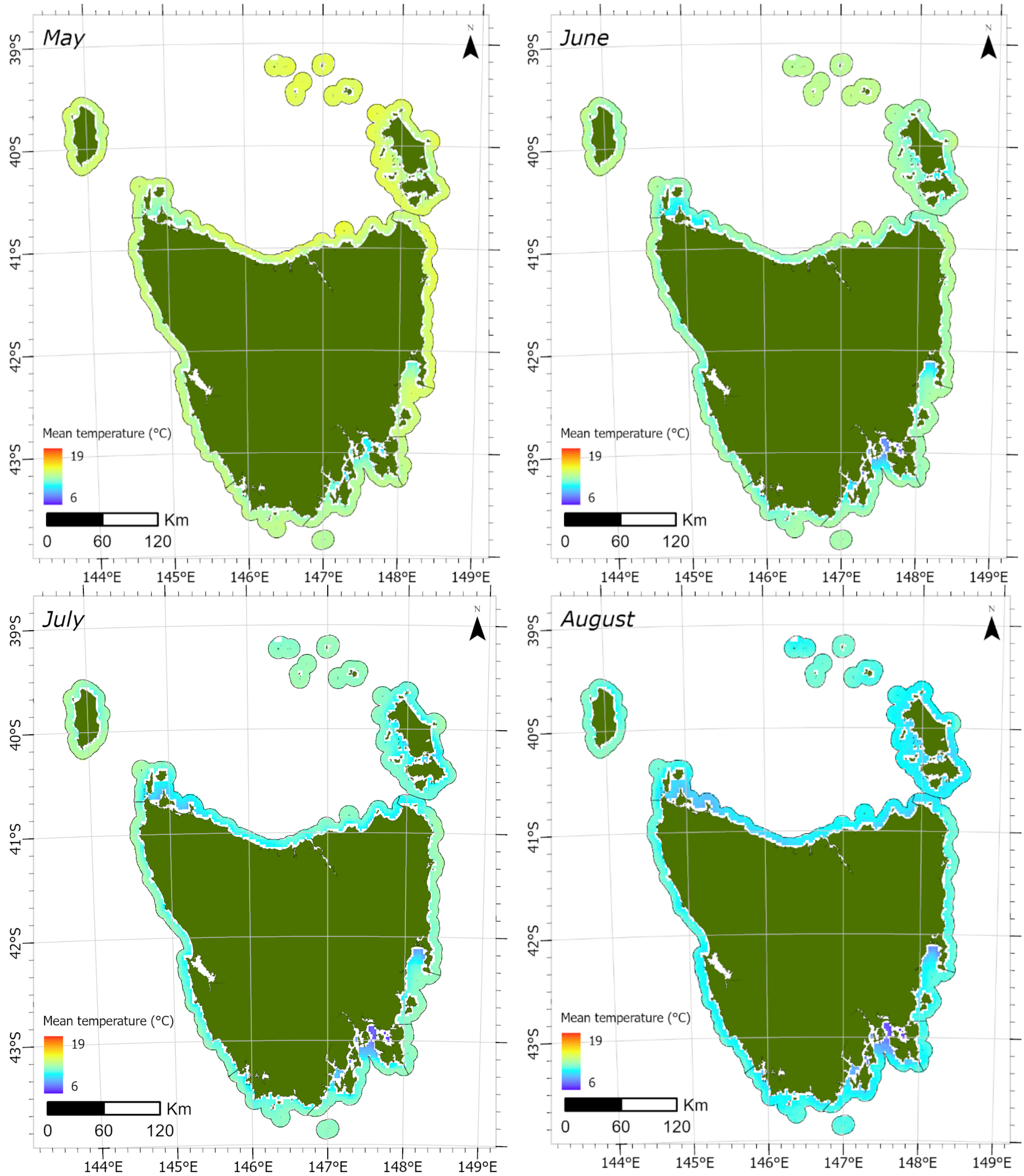

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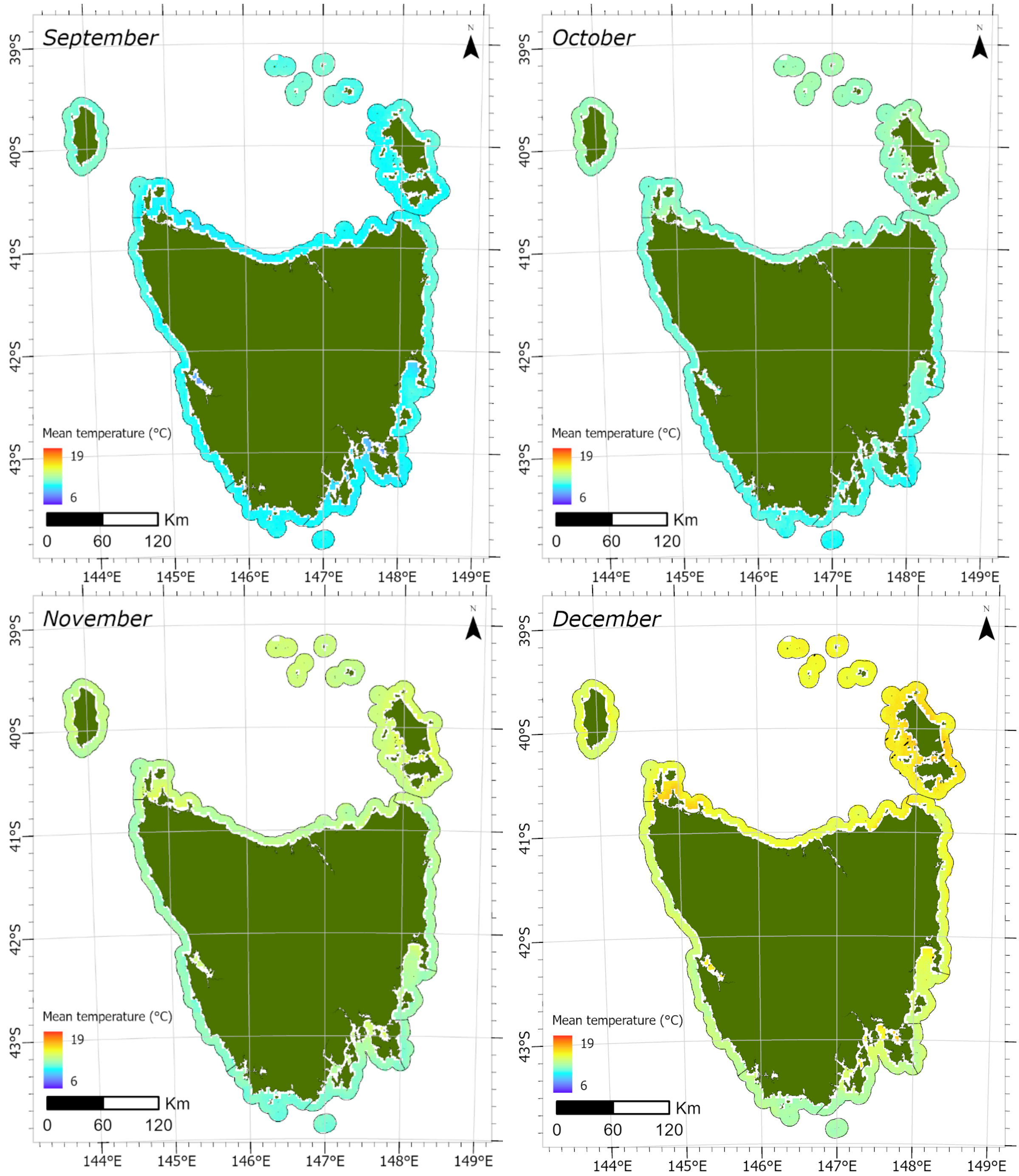
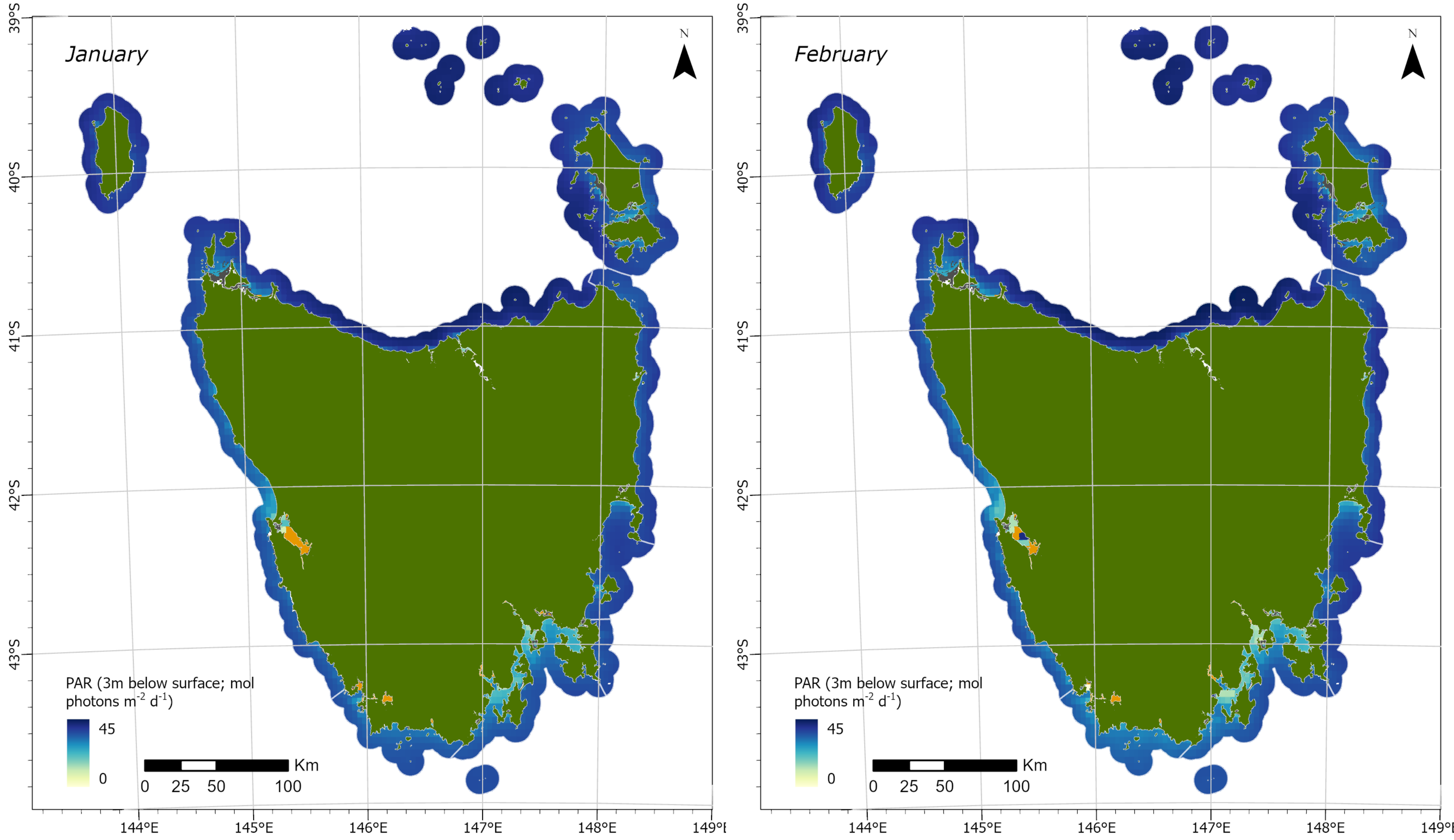


APPENDIX 4 – Monthly light availability Photosynthetically Active Radiation (PAR; mol photons m^{-2} d^{-1}) estimated at 3m below the surface based on monthly climatology (1998-2018) of surface PAR and average attenuation coefficients K_{PAR} (m^{-1}) using datasets provided by Gattuso et al. (2020). Shown in grey are areas where seabed depth < 3m; shown in orange is inferred 'Case 2 waters'.



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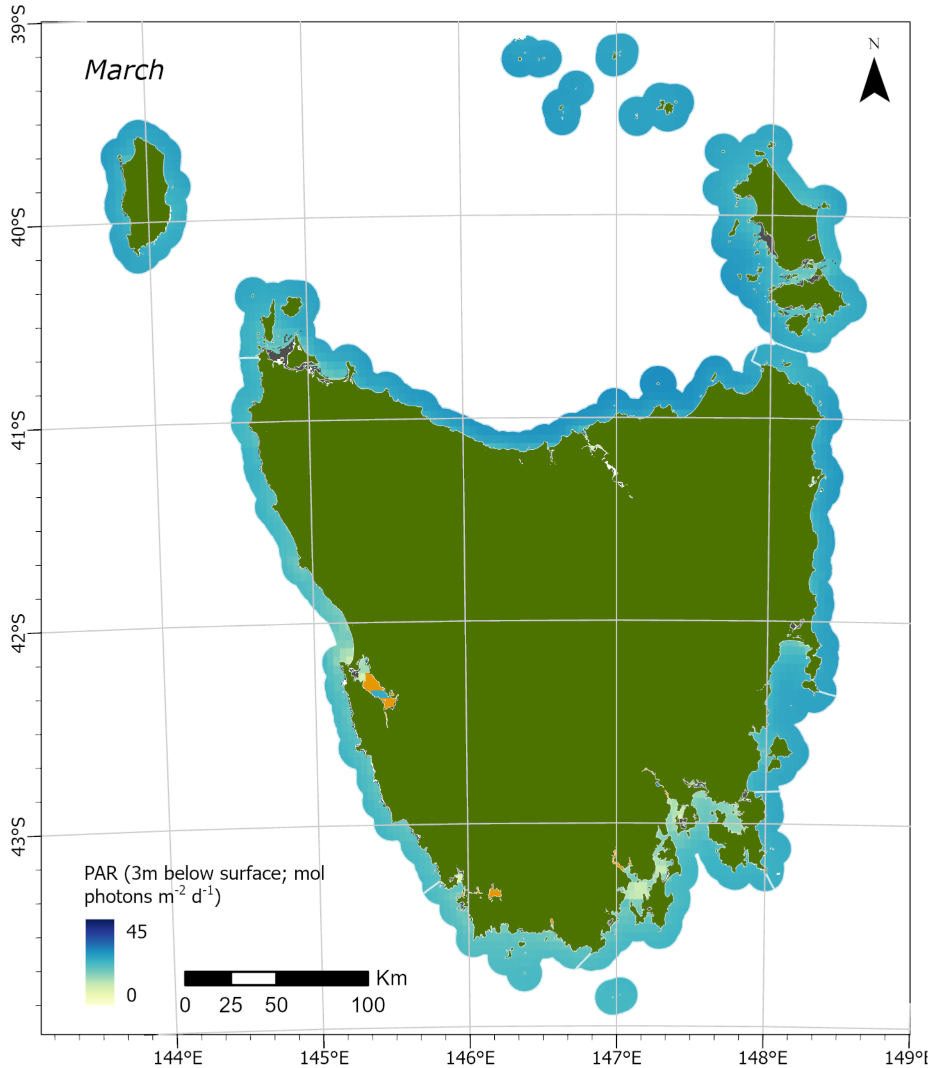

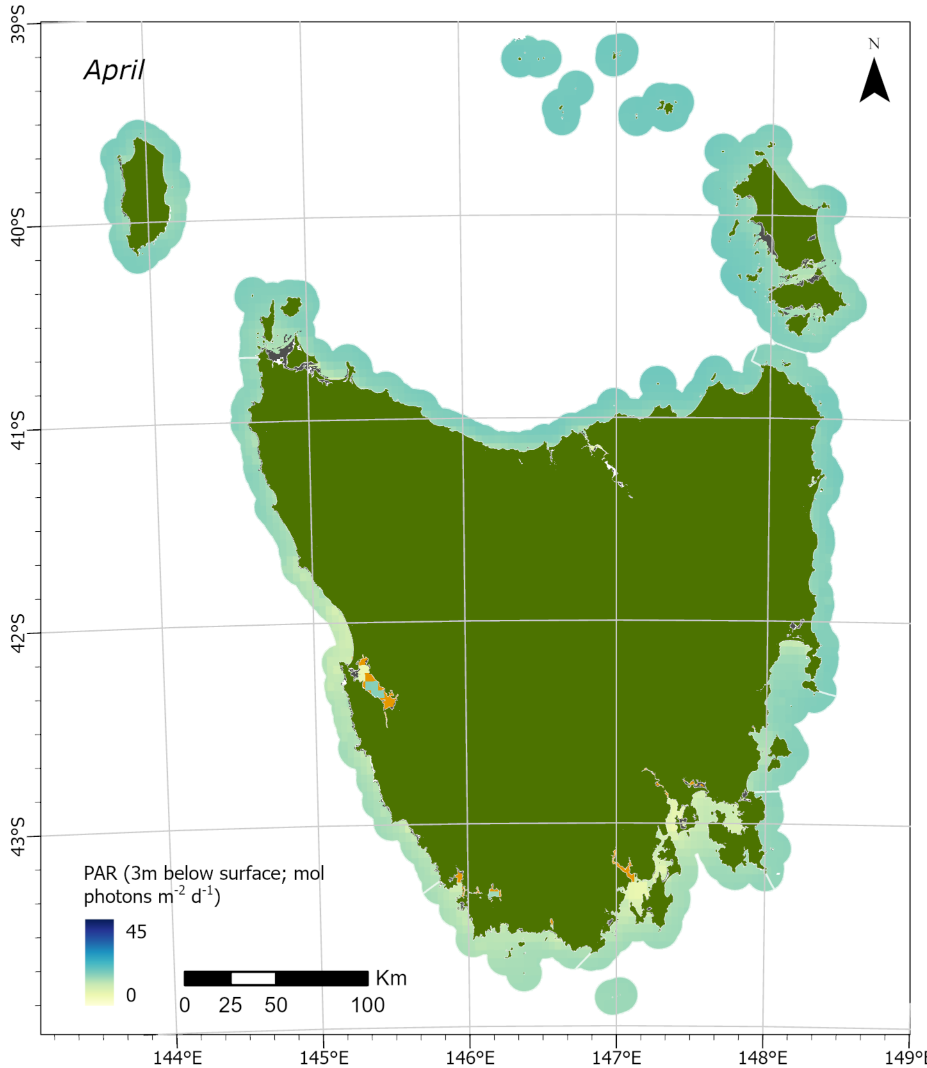

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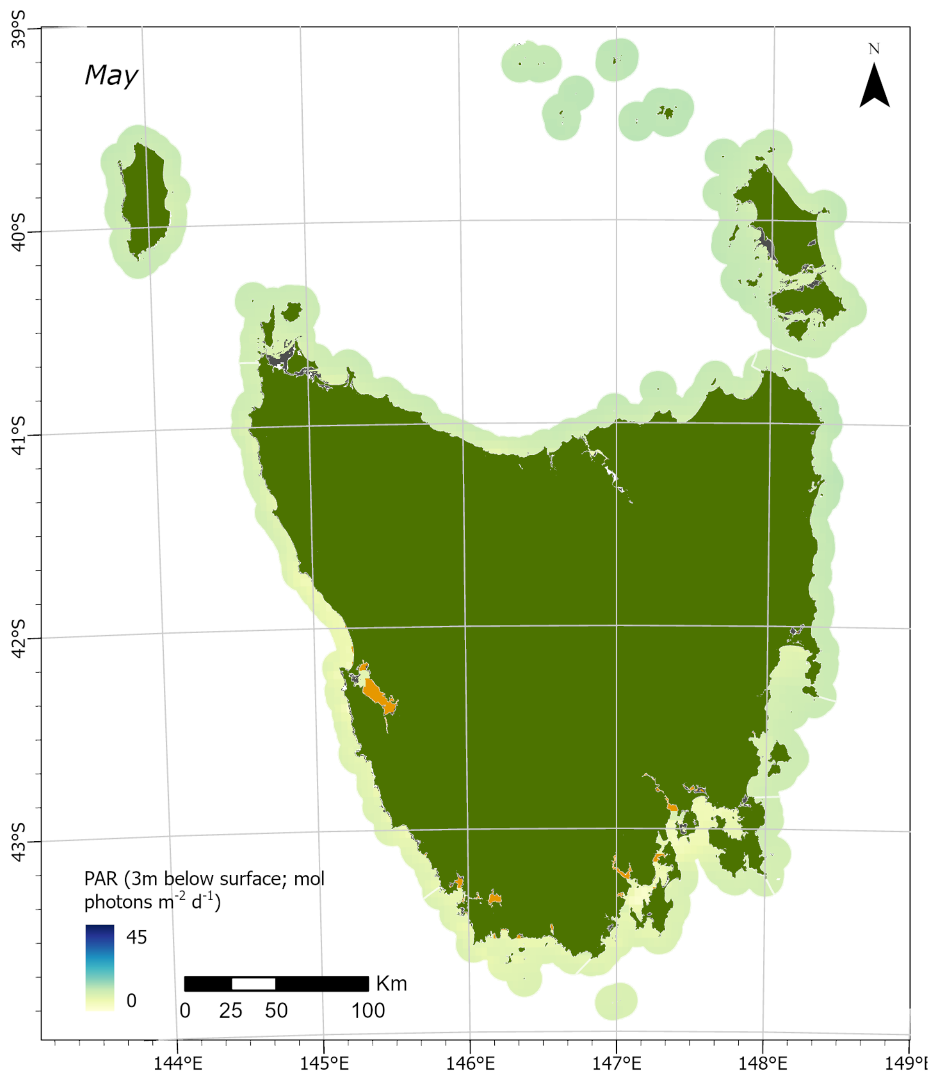

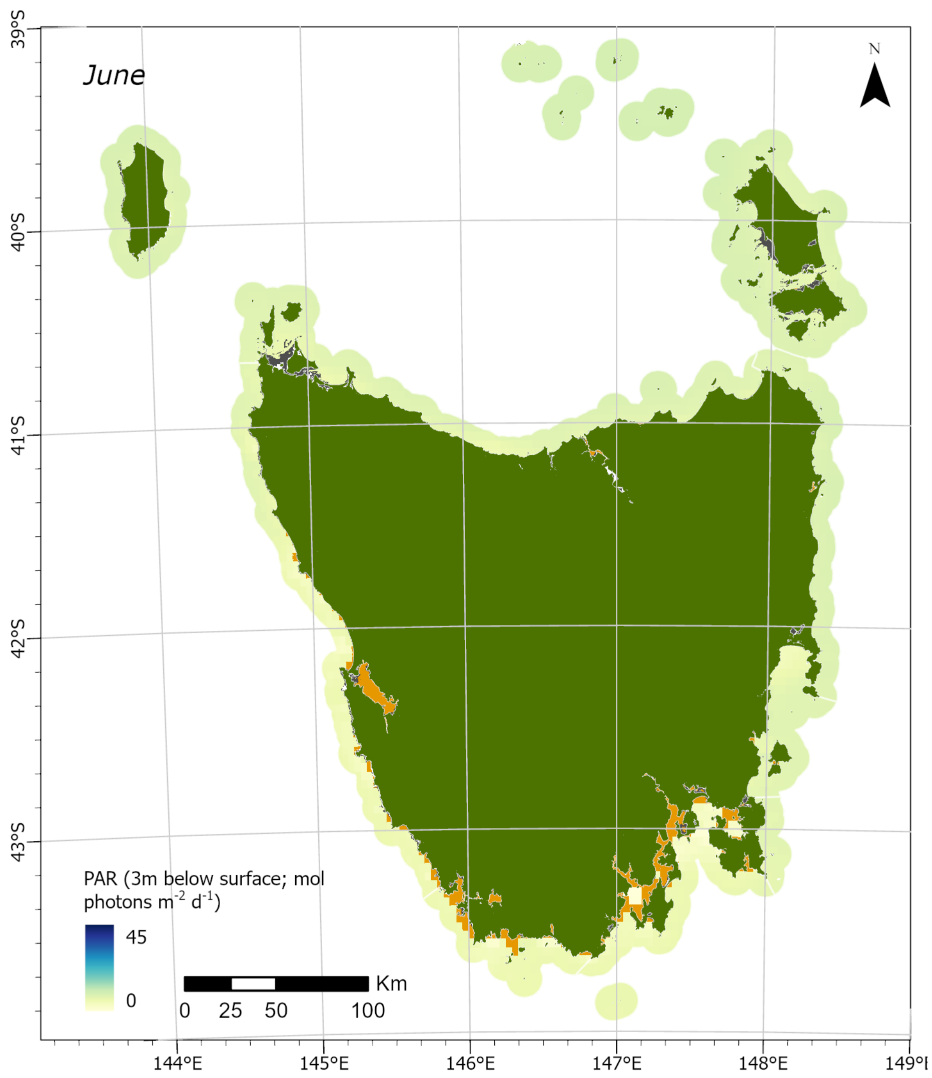

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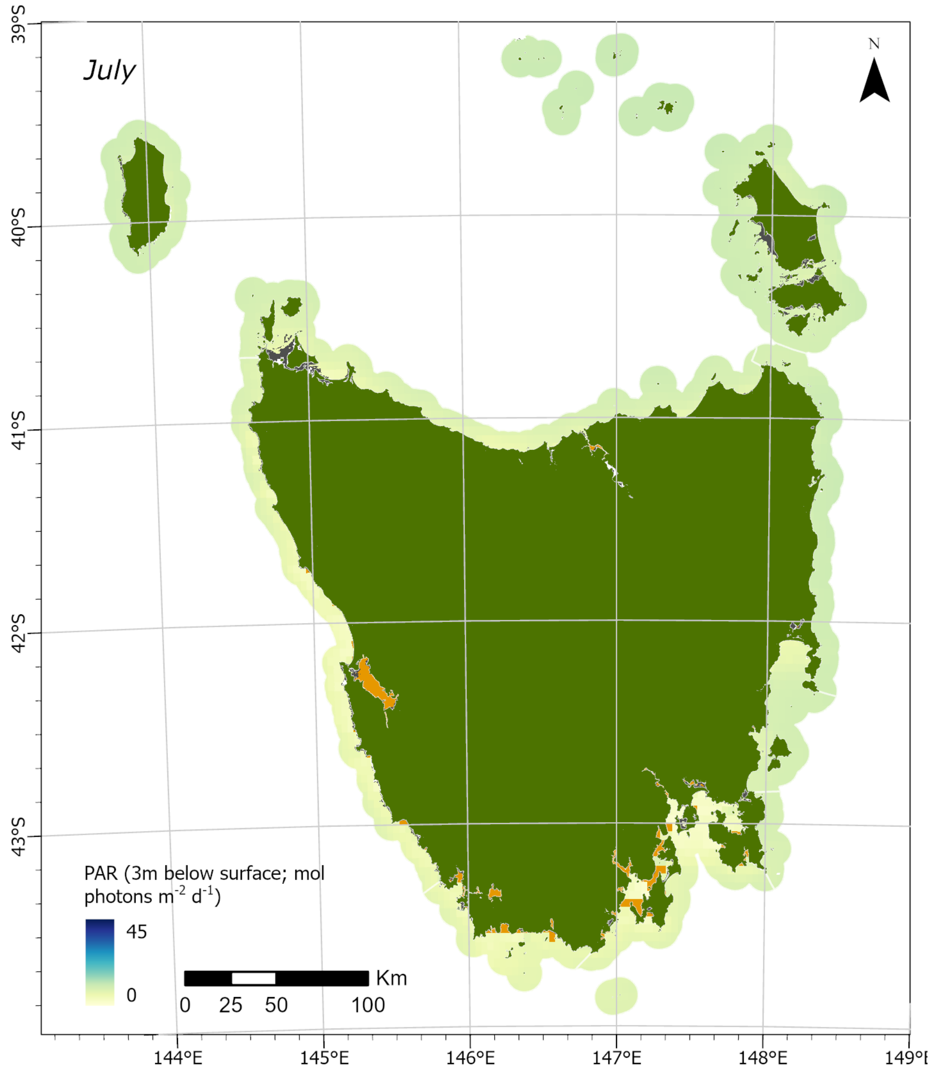

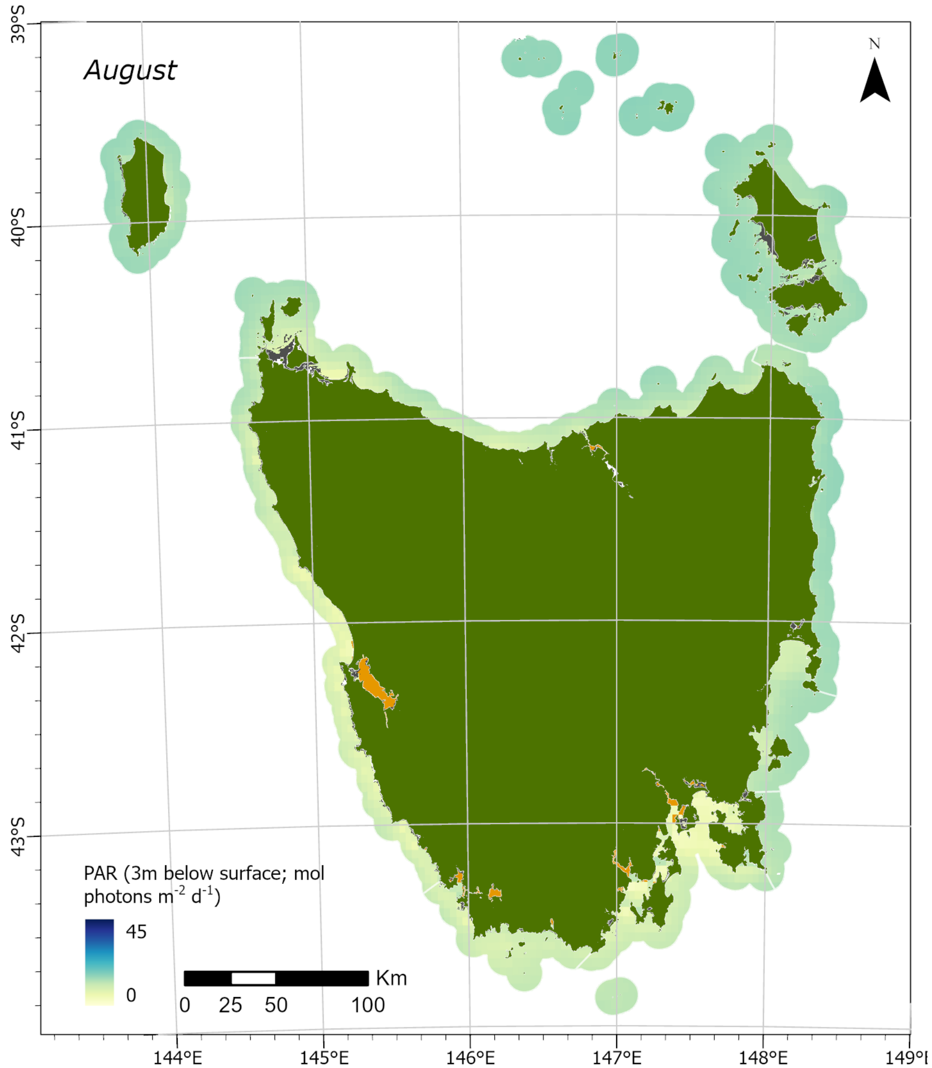

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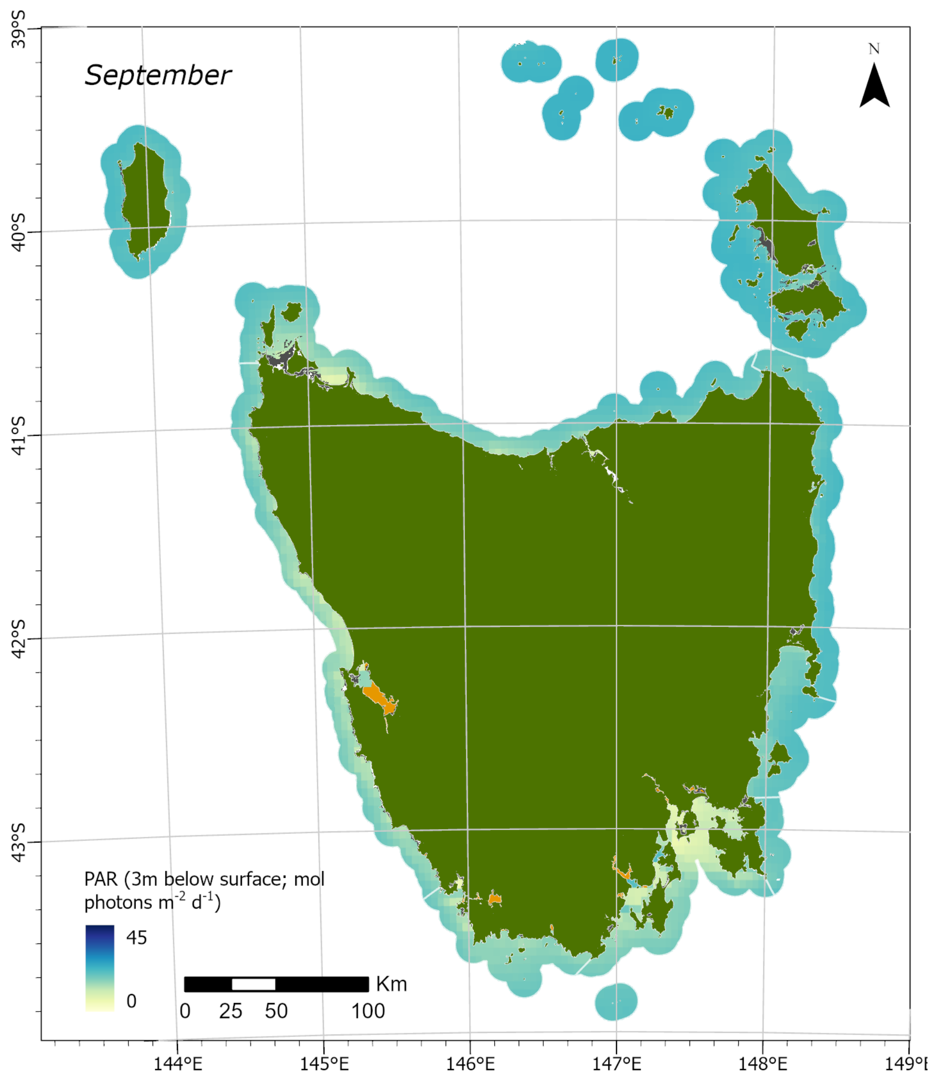

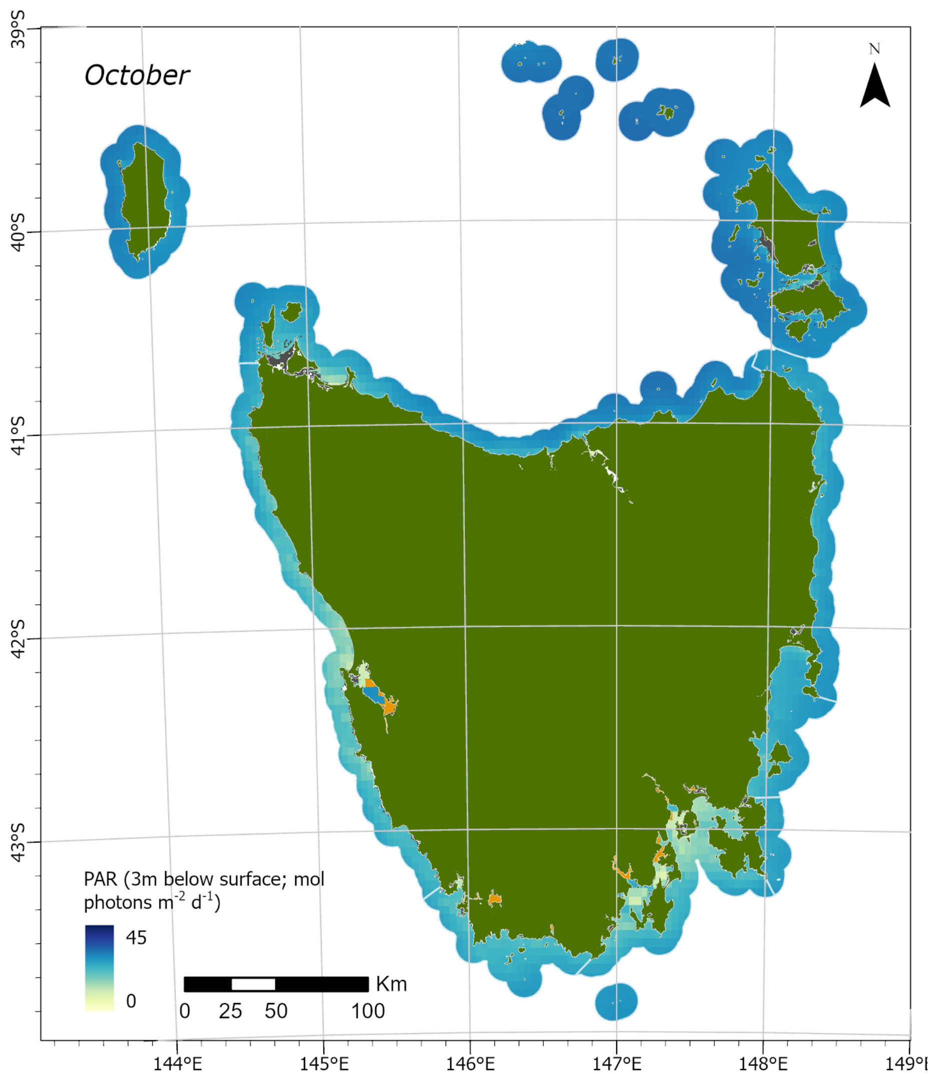

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