9.13 Phytoplankton/chlorophyll *a* in estuarine/coastal water (trophic state)

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Alternate attribute name: Trophic state using chlorophyll *a* concentration as a proxy for phytoplankton biomass in estuarine and coastal ocean waters.

State of knowledge of the "*Chlorophyll a (Chl.a)*" attribute

- Coastal-ocean (open coast): Good / established but incomplete.
- Estuaries: Medium / unresolved to Poor / inconclusive

National-scale satellite remote sensing of "surface" ocean colour and derived water quality attribute maps, of which chlorophyll *a* (Chl.*a*) is one, provides observations relevant to most coastal (< 12 nm limit) and some estuarine conditions, on moderate space (500 m) and time (days to decades) scales [32, 34]. A "coastal-ocean" ranking - good / established but incomplete - highlights on-going research effort and challenges in improving and confirming accuracy near coastlines in turbid waters, need for increased spatial resolution in many areas (10-100 m), and gap-filling and extrapolation techniques due to pixel failure (cloud cover, atmospheric correction, land adjacency and bottom reflection) [50]. Despite these challenges, observations on space and time scales aligned with natural dynamics in coastal and oceanic physical processes[16], provides long-term observation from mid-2002 on natural variability, suitable for establishing patterns and trends[37]

For the purposes of this document, "estuarine" waters require a distinction from – but are connected to – "coastal-ocean" waters, to reflect their more enclosed nature, connection to freshwater river inputs and their tidal/subtidal influence. For many estuaries, a medium / unresolved to poor / inconclusive ranking, highlights the porosity of location and time appropriate observations in consideration to their dynamic nature, particularly in connection with episodic and transient storm flow plumes [96, 24]. As outlined above, at times, in some areas, valid satellite observations in estuaries are useful and should improve with advancements in multiple satellite sensor resolutions and processing, with more in-water collections and sensor monitoring needed for calibration/validation in these complex and tidally dynamic water bodies, globally and nationally [3, 50, 49, 34].

Part A—Attribute and method

A1. How does the attribute relate to ecological integrity or human health?

Phytoplankton are microscopic algae (single-celled ‘plants’) living in the upper parts of the water which grow by photosynthesis depending on nutrient and light availability[52]. As all phytoplankton contain a green pigment Chl.*a* (mg m^{-3}), its concentration is commonly used as a proxy for algal carbon biomass (C – mg m^{-3}) which is often related to primary productivity rate (mg C m^{-2} d^{-1})[26].

Chl.*a* concentration is a widely accepted (globally and nationally) indicator of ‘overall’ biological productivity and “trophic state” (which was originally proposed for lakes[9]). Trophic state based on Chl.*a* has advanced into generally accepted classes across lake, estuarine and coastal waters (e.g., Table 1). Except where sub-surface Chl.*a* maxima occur, a near surface measurement of Chl.*a* is indicative of water-column integrated phytoplankton abundance and therefore its primary production particularly in ocean studies[4].

Some species of algae are toxic and are called Harmful Algal Blooms (HABs) and these can cause severe environmental and human health issues. A significant increase in the frequency of occurrence of HABs around the world has occurred, likely due to climate change and land-use changes[40, 113]. Adverse effects may include mass fish and wildlife death, human toxic reactions in consumed seafoods and in extreme cases, death. HABs are a subset of naturally-occurring blooms, and algal blooms in general can often be detected and tracked by satellite remote sensing of Chl.*a* (and other colour methods)[6]. With ground truth historical data (species ID), novel machine learning techniques have been used to identify specific events[45]. For local perspective, HAB occurrences and societal impacts for Australia and New Zealand have recently been reviewed [43].

Table 1: Trophic classes. Chlorophyll *a* concentration (Chl.*a*, mg m^{-3}) and water clarity (measured vertically as Secchi Disk depth - z_{SD}, m) ranges for descriptive trophic classes used in New Zealand lakes and estuaries; extended to include coastal-ocean conditions. Note: Microtrophic and Ultra-Microtrophic are not commonly present around New Zealand. Visibility can also be measured horizontally using a black disk (y_{BD}, m) which is broadly comparable to z_{SD}. Freshwater and Estuarine NPS states: A (Minimal); B (Moderate); C (High); D (Very High) – see footnotes.

Trophic class	Level	Lakes				Estuaries and coastal-ocean			
		Chl.a_{min}	Chl.a_{max}	z_{SDmax}	z_{SDmin}	Chl.a_{min}	Chl.a_{max}	z_{SDmax}	z_{SDmin}
Ultra-Micro	1	0.13	0.33	31	24	*0.01*	*0.05*	*80*	*40*
Microtrophic	2	0.33	0.82	24	15	*0.05*	*0.10*	*40*	*30*
Oligotrophic	3	0.82	2	15	7.8	0.1	1	30	8.5
Mesotrophic	4	2	5	7.8	3.6	1	3	8.5	4.0
Eutrophic	5	5	12	3.6	1.6	3	8	4.0	2.1
Supertrophic	6	12	31	1.6	0.7	8	12	2.1	1.6
Hypertrophic	7	31	~100	0.7	<0.1	12	~50	1.6	<0.1

Table 1 Footnotes: For New Zealand lakes, regional councils historically have used a seven-class trophic level index (TLI)[8], which has evolved into the trophic state (ecosystem health) system in the National Policy Statement for freshwater management (Freshwater NPS)[70]. The 4-attribute state (A-D) eutrophication system (minimal – very high) is also used in the New Zealand Estuary Tropic Index (ETI)[92] adapted[88] for four salinity estuary types. We extend the euhaline type estuaries (>30 ppt salinity) Chl.*a* ranges to include oligotrophic,

microtrophic and ultra-microtrophic classes guided by ocean studies [73] (Chl.*a* < 1 mg m^{-3}), as these can be associated with oceanic waters surrounding New Zealand. Secchi disk depths are included as a water clarity (visibility) guide only, being not as reliable as Chl.*a* for eutrophication as measures are impacted (reduced) by TSS and CDOM if present. Water clarity however is an important metric to consider as levels of irradiance drive the photosynthesis of primary producers. Water clarity is also important for sighted aquatic predators. Coastal marine eutrophication primary productivity (gC m-2 day-1) ranges for oligotrophic (< 100), mesotrophic (100-300), eutrophic (301-500) and hypertrophic (>500) systems that can be broadly associated with the trophic classes[76]. A worldwide compilation of 131 estuarine-coastal ecosystems also provides useful Chl.*a* context[11].

A2. What is the evidence of impact on (a) ecological integrity or (b) human health? What is the spatial extent and magnitude of degradation?

Estuaries. Globally, strong evidence of change and/or degradation in estuarine trophic states through eutrophication was established over 20 years ago[97] and more recently there is growing evidence and concern for HABs impacts[40, 113]. Nationally in New Zealand, we have limited direct evidence of the spatial extent or magnitude of degradation or adverse impacts resulting from changes in Chl.*a* in estuarine environments. Traditionally, monitoring Chl.*a* based on in water collections has been much more limited than long-term New Zealand river monitoring practices[96] because of difficulties with sampling estuarine/coastal systems at an adequate scale. Many in situ coastal monitoring sites should be considered as 'case study' indicators of local rather than national relevance [23, 31].

Degrading water quality at estuarine sites have been linked to changes in river flow and land-use (related to agriculture and urban land cover)[24]. In the absence of adequate long-term consistent and widespread monitoring of estuarine Chl.*a*, there has been increasing use of New Zealand estuarine trophic index (ETI) studies and tools for assessing eutrophic susceptibility and trophic state from alternative measured indicators [88] and use of predictions from Bayesian Belief Networks (BBN) when limited or no data are available [118]. Both ETI-based and BBN-based studies highlight many degraded and suspectable estuaries.

Coastal systems. Further offshore, a recent 2023 update on monitoring ocean health around New Zealand utilizing satellite Chl.*a* (with sea surface temperature and total suspended solids) documents a range of natural patterns (seasonal and interannual variability), states and range of trend directions (from mid-2002) in different areas around NZ[84]. This national scale assessment highlights the complexities of the choice of scale in spatial (site, area, region, water mass) and temporal (month, season, year, overall) interpretation of states, natural patterns, and change. A more comprehensive analysis of coastal hydrosystems[1], regions and water masses are needed to address spatial extent and magnitude of degradation, or change, to usefully assess potential impacts.

Coastal HABs are less well researched on a national scale, particularly in their relationship to Chl.*a*. However, species have been monitored since 1993 as part of the human health Marine Biotoxin Monitoring Programmes encompassing both commercial and non-commercial shellfish harvesting[93]. Their timely New Zealand review emphasizes the wide-ranging effects on commercial productivity and future directions and improvements needed in predicting movement and size of HABs,

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[1] We use the term "coastal hydrosystem" following [47] to describe coastal features that span a gradient from near coast freshwater lakes/wetlands to marine.

something that satellite Chl.*a* monitoring can augment. This is particularly relevant in consideration to the advancement of machine learning approaches which use these type of data[13].

Summary. The spatial extent and magnitude of estuarine and coastal degradation varies with factors like nutrient input, water circulation patterns, and local environmental conditions. In highly impacted areas, such as those with intensive agricultural or urban runoff, the degradation can be substantial, leading to widespread ecological disruption and public health concerns. These anthropogenic effects are also embedded in larger scale climate change influences on oceanic water masses. There is a critical role of Chl.*a* monitoring in assessing estuarine and coastal degradation across various space (from local to regional) and time (days to decades) scales and informs targeted mitigation efforts to address the root causes of ecosystem degradation and protect human health.

A3. What has been the pace and trajectory of change in this attribute, and what do we expect in the future 10 - 30 years under the status quo? Are impacts reversible or irreversible (within a generation)?

Estuaries. Change of Chl.*a* in estuaries is principally affected by land-use and riverine input, as well as modifications/activities in the estuaries themselves. The trajectory of change is directly influenced by river inputs and storm flow events carrying contamination loads and could be reasonably inferred or modelled using available tools[116]. Recovery responses will vary depending on catchment characteristics and the specific coastal hydrosystem. Managing and mitigating contaminant inputs, particularly those influencing algal growth such as macro-nutrients and light attenuation effects of suspended sediment, can modify eutrophication levels, reduce the potential for HABs and improve trophic status. It's crucial to recognize that the effectiveness of these measures is contingent upon the removal rates and buffering capacity of the system. Downstream effects in receiving environments may be reversible over time, but the rate of recovery is dependent on various factors including the extent of land-use practices and the resilience of the ecosystem. Additionally, the impacts of climate change on river hydrology are likely to have important long-term implications [12], with concurrent impacts on receiving environments such as estuaries.

Coastal systems. For the bulk of the coastal-ocean, where catchment influences are more “dilute” and open-ocean processes dominate, changes are principally due to the effects of climate change, with local modification due to land-use/riverine systems/coastal development. Changes to Chl.*a* in coastal systems due to climate variability and change are observable, ongoing, inevitable and unlikely to be reversible in the short term (decades). Earth-system models project changes to 2100 in coastal water temperature, mixed layer depth (light), macronutrients and primary productivity to varying degrees [57]. There remains uncertainty over how these large-scale climate changes will affect continental shelf (< 200 m) waters which are in the transition zone between land and oceanic influences. Climate-driven changes to coastal Chl.*a* will specifically depend as to how nutrient supply from river inputs and offshore upwelling/downwelling events, wave resuspension changes on light climate, mixed layer depths and water current changes will be modified under future conditions. Robust and accurate satellite observations of Chl.*a* across these physical process scales can be used for state of the environment monitoring for these areas.

Summary. Without significant intervention, trends in estuarine and coastal Chl.*a* are expected to persist and potentially intensify over the next 10 to 30 years. While targeted management efforts, such as reducing nutrient and suspended sediment inputs, offer some hope for reversal of changes in

Chl.*a* in some near shore coastal hydrosytems, the effectiveness and pace of recovery depend on various factors, including the severity of degradation and the scale of interventions. While some impacts may be reversible with concerted action, prolonged or severe degradation could result in partially irreversible effects within a single generation, emphasizing the need for proactive measures to safeguard coastal ecosystems and human well-being.

A4-(i) What monitoring is currently done and how is it reported? (e.g., is there a standard, and how consistently is it used, who is monitoring for what purpose)? Is there a consensus on the most appropriate measurement method?

In situ (discrete) sampling. In-water measurement methodologies for Chl.*a* have been rationalised by the National Environment Monitoring Standards (NEMS) for discrete (in situ) sampling and analysis of coastal water quality, including Chl.*a*[72]. Standardization of measurement methods ensures consistency and comparability of data across different regions, but historical data prior to this relatively recent (2018) implementation differs making assessment of change problematic. In these in situ/laboratory-based analyses of water quality, typically, particles from a known volume of collected water are concentrated onto filter paper, extracted with acetone and the concentration determined against Chl *a* standards using either fluorescence or spectrophotometric methods (mg m^{-3}).

For New Zealand, regular monitoring of Chl.*a* is primarily conducted by Regional Councils, responsible for monitoring specific coastal areas within their jurisdictions and to their most relevant need, mainly for estuarine water quality and summer period recreational swimability guidance. They provide annual[48, 79] and multi-year SOE reports[28, 80, 27], with their own regional flavours and no national consistency in reporting. Regional sampling effort is guided by the Department of Conservation (DOC) Policy 21: “Enhancement of Water Quality” as part of the 2010 New Zealand Coastal Policy Statement (NZCPS) where it has deteriorated[77]. The Ministry for the Environment (MfE) oversees national environmental monitoring programs which use Regional Council data to fund broader insight[23, 31], jointly with StatsNZ in “Our marine environment 2022” reporting series[71].

The Department of Conservation (DOC) is responsible for the implementation, management, and monitoring of 44 marine reserves, and provides guidance in the Marine Monitoring and Reporting Framework (MMRF) Theme 6: Water quality [18]. MMFR is designed for both local and national stakeholders to guide long-term marine monitoring taking a whole system approach.

Coastal and estuarine water quality data are available through some Regional Councils website, with curated data nationally reported as summaries or aggregates at: LAWA (Land Air Water Aotearoa): Estuary Health [58], but this is yet to include water quality attributes, instead linking to StatsNZ as states and trend indicators[101]; and DOC in the “Estuaries spatial Database”[19]. These are compiled from the most recent MfE funded analysis[31].

Autonomous field instrumentation. NEMS protocols for monitoring Chl.*a* by other methods do not currently exist for in situ deployable sensors such as Chl.*a* fluorometers[119]). The accuracy of observations of estuarine/coastal Chl.*a* by autonomous instrumentation relies on robust relationships between in-water Chl.*a* and fluorescence [83] which is a field of active research overseas but less so in New Zealand.

Remote sensing. Satellite (remote-sensing) technology for observing water colour in specific wavebands (e.g., remote sensing reflectance Rrs[115]) in coastal systems has existed since 1997 (4 km) with reasonable spatial resolution (0.5-1 km) since 2002. Satellite methods of observing estuarine/coastal Chl.*a* rely on relationships between in-water Chl.*a* concentrations and water colour[41]. For satellite Chl.*a* maps, empirical “band-ratio algorithms” (e.g., blue and green Rrs) has proven effective for open-ocean and coastal waters where phytoplankton and its by-products primarily contribute to colour, so called Case 1 conditions[41] and [78]. However, in turbid coastal waters (so called Case 2) Case 1 algorithms are inaccurate due to the presence of other light attenuating components, such as suspended sediments and coloured dissolved organic matter from rivers, shore erosion and wave resuspension events. Case 2 waters require more complex “semi (or quasi) analytical algorithms (QAA)” to tease apart the contributions of absorption and scattering characteristics of each component, prior to determining their levels for improved accuracy[60, 61, 37].

The Ministry for the Environment (MfE) jointly with StatsNZ has recently started using satellite observations for longer temporal and broader spatial Chl.*a* assessments in coastal systems[[86, 84]). NIWA-SCENZ (Seas, Coasts and Estuaries New Zealand) provides web-access to all satellite water quality attributes for the NZ coastal-ocean from mid-2002 in weekly, monthly, seasonal, and yearly aggregate states, climatologies and anomalies [85, 37]. Satellite monitoring is expected to advance state of the environment assessment and reporting with future research effort and national support, to provide improved national maps for standard, consistent monitoring of Chl.*a*, with a range of other water quality attributes and analytics (e.g., climatologies, anomalies, trends)[32]. MPI have also funded recommendations in ocean indicators (including Chl.*a* and primary producers) as part of the Atmospheric and Ocean Climate Change Tier 1 Statistic[87].

Other monitoring. Aquaculture New Zealand relies on clean coastal environment and sustainable farming practices, with expected future growth in offshore (open ocean) farming, particularly with Integrated Multi-Tropic Aquaculture (ITMA)[103]. In some cases aquaculture monitoring datasets are not be freely available, but they form part of long-term monitoring requirements by the Ministry of Primary Industries (MPI), which have funded a range of water quality monitoring guidelines (including Chl.*a*) and standards for the aquaculture industry, including bivalve shellfish (mussels and oysters)[51], salmon in Marlborough Sounds[25] and open-ocean finfish culture[38]. Additionally, Fisheries NZ (MfE) have recently completed (Aug-23) year three review of National Environmental Standards for Marine Aquaculture (NES-MA) recommending inclusion in regional coastal plans and developing best practice guidelines on the scope and scale of monitoring.

Appropriate observation of Chl.*a*, primary producers and HABs are needed for monitoring the “Carrying capacity” of a system, particularly in consideration to bivalve (mussel and oyster) filter feeders on trophic food sources[68], finfish farm eutrophication and potential HAB effects[30], and aquaculture impacts in general which are of environmental, social, economic, and cultural concern globally[7]. Multi-scaled sampling using in situ monitoring (water collections and moored instrumentation) with satellite observations are all required to capture fit-for-purpose Chl.*a* dynamics across different scales.

A4-(ii) Are there any implementation issues such as accessing privately owned land to collect repeat samples for regulatory informing purposes?

In situ (discrete) sampling. The practicality, feasibility and cost effectiveness of in situ methods of monitoring Chl.*a* is dependent on the characteristics of the coastal system of interest. The activity of in-water sampling in estuaries and the coastal-ocean is challenging, that usually requires trailered boat surveys (< 6m), a qualified skipper with local knowledge, trained staff and all the appropriate health and safety requirements for the activity. Weather provides challenges of its own for regular, large-area, coastal sampling. Consequently, sampling is often biased to calmer periods unless suitable research vessels are available (typically in offshore coastal waters), examples of which are mentioned in a 15-yr Firth of Thames seasonal samplings[36]. These medium sized vessels (15-25m) with several crew and on-board, food, and accommodation, ensure sampling is achieved. Due to high costs, often these are part of larger area surveys that might be combined with moored instrument deployments, recovery, cleaning, servicing, and redeployment. Larger oceanographic vessels (~75-100m) such as the NIWA Tangaroa may be required for coastal-ocean surveys on the continental shelf or deeper waters with voyage plans supporting multiple projects and objectives for multi-week samplings.

In New Zealand, where a considerable portion of the coastline may be privately owned, gaining access permissions for sampling from the shore may be challenging, especially if landowners are unwilling to grant access or if there are legal complexities regarding property rights. Additionally, logistical challenges such as navigating rugged coastal terrain, coordinating sampling schedules with landowners, and ensuring the safety of monitoring personnel in remote or inaccessible areas further complicate the monitoring process. These implementation issues can hinder the collection of consistent and representative data, potentially impacting the accuracy and reliability of regulatory assessments and decision-making processes.

Remote sensing. Satellite remote sensing data relies on availability through the earth-observation community worldwide, as well as specifically the contributions of the NASA Goddard Space Flight Center and the MODIS project for access to remote sensing globally. Without their support, access to satellite data would not be possible. Much of the imagery is provided by the Land Atmosphere Near-real-time capability for EOS (LANCE) system and the services offered by the Global Imagery Browse Services (GIBS), both operated by the NASA/GSFC/Earth Science Data and Information System (ESDIS), funded by NASA/HQ. The NOAA Center for Satellite Applications and Research (STAR) the Ocean Biology (OB) group, the European Union Copernicus Marine Environment Monitoring Service (CMEMS), and the European Space Agency (ESA) Ocean Colour (OC) Climate Change Initiative (CCI) all provide satellite data for free. At present for NIWA-SCENZ, we are using MODIS-Aqua data from NASA but will need to utilise and incorporate other ocean colour sensors such as VIIRS (NASA) and Sentinel-3 (ESA) in future.

A4-(iii) What are the costs associated with monitoring the attribute? This includes up-front costs to set up for monitoring (e.g., purchase of equipment) and on-going operational costs (e.g., analysis of samples).

In situ (discrete) sampling. The laboratory analytical cost for a Chl.*a* analysis are small (about $15 per filter, $20 if filtration needed) compared to the overall cost of sample collection. The overall cost of monitoring Chl.*a* in New Zealand estuarine and coastal systems at the national scale using in situ sampling is obviously dependant on how many samples are needed. Specifically, the costs depend on how many sites and how often sampling is needed. This has not yet been properly assessed, but it is clear that current levels of in situ sampling are inadequate in both regards: too few sites are monitored, and the sampling is too infrequent to account for the variability. Sampling from the shore, jetties, or wharfs at high tides, in many systems, does not adequately capture its variability.

See the relevant section in the discrete water quality sampling and testing Vol. 4 (Coastal) NEMS[72] for further advice and details on this type of sampling.

<u>Autonomous field instrumentation</u>. Autonomous field instrumentation may provide a more cost-effective monitoring system for Chl.a than in situ (discrete) sampling but this is not proven. A comparison of costs will need to include upfront costs to purchase of monitoring equipment such as fluorometers, spectrophotometers, water quality probes, and boats or vessels for sample collection and staff time. Additionally, investments may be required for establishing monitoring stations, deploying sensors on buoys or moorings, and acquiring laboratory facilities for sample processing and analysis (for calibration/validating in situ instrumentation). Other recurring expenses may include maintenance and calibration of monitoring equipment, quality control measures, data management software, and communication infrastructure for transmitting real-time data. Ideally, autonomous field instrumentation would be combined with (seasonal) surveys to combine time-series measurements with a suite of collections of other environmentally relevant parameters and scientific objectives (e.g., Hauraki Gulf time-series).

<u>Remote sensing</u>. Suitable satellite data for monitoring estuaries and coastal Chl.a at the New Zealand national scale is available for free from NASA, NOAA and EU (Copernicus). There is a relatively-small ongoing cost within New Zealand to access, quality control/validate/calibrate (using local knowledge/measurements), and apply the data for tracking change in Chl.*a*. Maintaining New Zealand expertise in coastal remote sensing to get the most out of the free-to-air satellite data requires ongoing funding which has no long-term stable funding.

A5. Are there examples of this being monitored by Iwi/Māori? If so, by who and how?

The Ngā Waihotanga Iho (Estuary Monitoring Toolkit) is a useful example of the developments relevant the collection of estuary attributes[91, 105, 75]. While collections and observations of Chl.*a* are not directly included at present, they could be considered in the future to provide information on aspects of “decline in water quality, for example reduced water clarity, contamination of water and kaimoana due to runoff of human and animal waste”. This has particularly relevance to potential changes in trophic states, HABs, and human health.

The observation of phytoplankton (as indicated by *Chl. A*) would also be important in their relationship with kaimoana, in particular mātaitai (shellfish) are part of the holistic approach to understanding ecosystem health in estuaries. That is beyond, an indicator for decline in water quality (mentioned above), they are an indicator of the benthic-pelagic coupling, and thus advocate for supporting a healthy population size and structure of taonga species, such as mātaitai (shellfish), which has been assessed in engagement with mana whenua in Otago [[120]].

There are other “in-direct” observational methods that could be more practical for Iwi/Māori and citizen science in general. For example, Munsell water colour standards [15] and observations can be used as a proxy for Chl.*a* and trophic state that also provide a more direct aesthetic connection to human perception[114]. Supporting this approach are efforts to use water colour aspects from satellite remote sensing[109, 111, 62, 110] which can provide a connection between the different types of monitoring effort across different scales.

A6. Are there known correlations or relationships between this attribute and other attribute(s), and what are the nature of these relationships?

There are many correlates of Chl.a in coastal and estuarine waters of relevance to understanding change in water quality for the purposes of improving environmental management, stewardship and wealth creation. Chl.a in estuarine and coastal systems is intricately linked to attributes including: (1) turbidity/scattering; (2) total suspended solids; (3) water colour (Munsell water colour standards, Apparent Visible Wavelength); (4) water clarity (visibility, light attenuation, Sechhi depth); (5) macro-nutrients); (6) Dissolved Oxygen Concentration; (7) Faecal contamination; (8) primary production by phytoplankton growth; (9) light reaching the seabed (related to benthic autotroph primary production). The exact relationships between Chl.a and these other factors depend on complex ecological interactions and environmental processes[53]. High Chl.*a* can reduce water clarity[35], influence dissolved oxygen dynamics[117], and serve as a proxy for phytoplankton biomass and diversity[94]. These interrelationships highlight the interconnected nature of coastal ecosystems and the importance of considering multiple attributes in monitoring and managing coastal water quality and ecosystem health[53].

Part B—Current state and allocation options

B1. What is the current state of the attribute?

In situ (discrete) sampling. The current state of change in estuarine Chl.*a* at the national scale is poorly understood based on direct observational measurements (in situ sampling and/or autonomous field instrumentation). Regional Council monitoring sites are clustered unrepresentatively around urban centres (about 350 sites), and many types of estuaries (and likely types of change) are under-represented spatially across the system[23, 31]. Sampling frequencies at these sites (typically monthly) are also inadequate to have the statistical power to capture whare are usually small long-term changes and trends against a backdrop of substantial variability on time-scales from minutes to years. Despite these challenges, the latest MfE-funded national analysis in 2021, compiled from a curated subset, documents a mixture of current states and direction of any trends in Chl.*a* with high variability in ETI classes [31]. A wide range of changes based on this analysis is not unexpected because of regional differences and natural spatial and temporal variability within each system. StatsNZ updates and publishes a higher-level assessment on their website [102] (e.g., “For nine coastal and estuarine water quality measures, more sites had improving trends that worsening trends (2006-2020)”. While this provides a degree of national rationalisation, it highlights inadequacies and challenges of sampling and interpretation across different coastal hydrosystems.

Remote sensing. For the coastal-ocean (excluding may small estuaries), satellite Chl.*a* provides a more complete assessment, but not one that is without it’s own limitations in terms of detecting and understanding the drivers of change in Chl.*a* [84]. From mid-2002 to early-2023, satellite studies show that Chl.*a* has increased along the mid-lower North Island and all of South Island, especially during winter, suggesting higher productivity likely due to nutrient inputs or upwelling. Conversely, Chl.*a* has decreased along the west coast of Northland and northeast New Zealand shelf, indicating potential issues with productivity possibly linked to changes in nutrient availability or environmental factors. Lower-than-normal Chl.*a* during Marine Heatwave (MHW) events along the west coast of

South Island in December 2017 to March 2018 and December 2022 to January 2023 may signify reduced productivity, necessitating further investigation into its causes and potential impacts on marine ecosystems and fisheries. The satellite-observed trends in Chl.a may also help to prioritise in situ sampling and design a more representative system of sentinel coastal sites.

A recent update in satellite Chl.*a* trends (up to Aug-2023) was provided as part of a Cyclone Gabrielle (Feb-2023) impacts on fisheries, for a long-term context[59]. Web access to data is provided through the NIWA-SCENZ[74] project page application "Trendy-SCENZ"[74], which illustrates national scale maps of Chl.*a* trend directions (absolute and percentage of climatology median) per decade, and statistical likelihoods [67]. Web access of national scale maps allows users to interactively explore the complex spatial patterns ranging from broad coastal-ocean (1000 km) to estuary (0.5 km) scales, highlighting the significance of delineating aggregation boundaries for precise interpretation.

B2. Are there known natural reference states described for New Zealand that could inform management or allocation options?

Identifying natural reference states for Chl.*a* in New Zealand's estuaries is challenging and would need to be inferred from pre-European settlement conditions, remote and pristine comparable estuaries, or indigenous ecological knowledge. Regional Councils are facing challenges in determining appropriate reference states for State of the Environment (SOE) reporting, given that many coastal hydrosystems have undergone significant modifications due to landscape changes over time. These changes would align to pre-human reference states (before 1200), modifications during the pre-European period post-Māori burning (1840), and further modifications up to the present post-European settlement era[112]. Hindcasting estuary ecological states (ETI scores) using sediment cores is a promising method for gaining insight into identifying step changes and reference states of attributes of interest[42]. Satellite Chl.*a* in coastal-ocean waters, particularly in regions adjacent to remote and pristine coastlines (if any can be identified at present), may also reflect reference states, however, a thorough analysis is yet to be made. Coastal regions would need to consider adjacent coastal catchments, water mass types, physical oceanic processes, and seasonality to determine reference states and natural variability.

B3. Are there any existing numeric or narrative bands described for this attribute? Are there any levels used in other jurisdictions that could inform bands? (e.g., US EPA, Biodiversity Convention, ANZECC, Regional Council set limit)

The Australian and New Zealand Environment and Conservation Council (ANZECC) and the Australian Water Quality Guidelines for Fresh and Marine Waters provide guidance on Chl.*a* for maintaining ecosystem health, and "precautionary" default trigger values of 4 mg m^{-3} for estuaries and 1 mg m^{-3} for marine due to lack of data[1]. This was advanced in 2016 to a New Zealand relevant Estuary Trophic Index in 2016[92], adapted in 2020[88] and an extension proposed in 2022 to include coastal-ocean waters[33](Table 1). While there may not be universally (globally) established bands for Chl.*a*, some regional councils may set different limits or guidelines based on water quality standards or ecosystem health targets in their region, particularly in consideration to returning to reference state conditions.

B4. Are there any known thresholds or tipping points that relate to specific effects on ecological integrity or human health?

There are not any known "general" (i.e., national scale) thresholds or tipping points in Chl.*a* that relate to specific effects on ecological integrity or human health. It is likely that the significance of a change or particular level of Chl.*a* depends on the particular characteristics of the estuary and coastal hydrosystem, including the ecosystem products and services that humans value in that system. New Zealand lacks an understanding of appropriate "general level" national-scale Chl.*a* tipping points in estuaries and the coastal-ocean, except for ongoing efforts to streamline eutrophication thresholds and define the four attribute states outlined in Table 1, which aid in identifying states of concern. This underscores the importance of fundamental research in understanding processes as well as ecosystem goods and services in natural estuarine/coastal systems, as predicting tipping points is impossible without the underlying understanding[5].

B5. Are there lag times and legacy effects? What are the nature of these and how do they impact state and trend assessment? Furthermore, are there any naturally occurring processes, including long-term cycles, that may influence the state and trend assessments?

Yes, lag times and legacy effects can significantly impact state and trend assessments of Chl.*a* in estuarine and coastal waters. Legacy effects occur when past disturbances or inputs continue to influence Chl.*a* after the cessation of the initial driver. For example, changes from historical land use practices may continue to affect nutrient and sediment inputs in estuarine/coastal systems for years or decades after the change in land use occurred, contributing to change in Chl.*a*, potential eutrophication and algal blooms. These lag times and legacy effects can complicate state and trend assessments by masking short-term changes or obscuring the true extent of ecosystem degradation. Furthermore, climate variability and change, such as the El Niño-Southern Oscillation (ENSO) or the Pacific Decadal Oscillation (PDO), co-occurring with changes to land use or coastal development can influence Chl.*a* through changes in sea surface temperature, precipitation patterns, and ocean circulation, leading to variability in state and trend assessments over long-term cycles. Accounting for these complicating factors (multiple stressors) is needed to accurately interpret Chl.*a* data and inform effective management and policy decisions in coastal environments. It has been estimated that unambiguously separating the signal of anthropogenic climate change from decadal variability on ocean Chl.*a* and productivity may take 20-50 years of satellite observations so we are only just beginning to have time-series long enough to do this around New Zealand[44].

B6. What tikanga Māori and mātauranga Māori could inform bands or allocation options? How? For example, by contributing to defining minimally disturbed conditions, or unacceptable degradation.

Tikanga Māori and mātauranga Māori offer valuable insights for defining coastal ecosystems states, examples being the connection of location knowledge and palaeoecology[63], and supporting the sustainability of aquatic biological heritage[2]. These can relate to the productivity (Chl.*a*) of local coastal waters, for cultural, social, economic, ecological and ecosystem services, including customary harvest and health of keystone or kaitiaki species and taonga associated with marine resources.

Part C—Management levers and context

C1. What is the relationship between the state of the environment and stresses on that state? Can this relationship be quantified?

Macro-nutrients, light availability (which depends in part on suspended sediment), water-column structure and temperature are the main drivers of Chl.*a*, trophic state and HABs. Nutrient and sediment are affected through various pathways of contaminant transport (dissolved macro-nutrients and suspended sediment) either from adjacent land runoff and river discharge (particularly during stormflow events) or from coastal physical process such as mixing and upwelling transport of oceanic nutrients[10, 11]. Many of the drivers of Chl.*a* can be quantified at a local scale with adequate observation, knowledge and understanding on various time-scales (tidal, episodic, seasonal, interannual, decadal). Location-specific relationships and dynamics are linked to coastal land-catchment properties and inputs of river water quality[98, 54, Larned, 2020 #4202], the type of hydrosystem[47], and their physical oceanographic process connections[104]. Spatial maps using ecological Marine Environment Classification (MEC)[99] and marine Ecosystem Services (ES)[107] can provide useful context information at the national scale.

C2. Are there interventions/mechanisms being used to affect this attribute? What evidence is there to show that they are/are not being implemented and being effective?

C2-(i). Local government driven

A significant portion of nutrient loading in coastal waters originates from urbanization and pastoralization of adjacent land based on robust evidence of their effects on freshwater ecosystems[56] and recent analysis on nitrogen loads to aquatic receiving environments in comparison to regulatory criteria[100]. Regional Council interventions have hence tended to prioritize land-based actions to first enhance freshwater quality. Regional Councils face resource constraints while balancing obligations to monitor the effectiveness of regional policies and plans under the Resource Management Act (RMA), the MfE National Policy Statement for Freshwater Management (NPS-FM), the New Zealand Coastal Policy Statement (NCPS) and to meet community and tangata whenua priorities. These often conflict with the approaches necessary for a national overview of the state of the environment[39, 106]. The recent Envirolink report on challenges and needs of Regional Councils in freshwater monitoring[106], underscores the pressing need for increased scientific investment in environmental monitoring at the national scale. Key priorities included better quantification of land-use impacts, establishment of infrastructure to support community monitoring efforts, advancement in modelling techniques, and the development and utilization of remote sensing and environmental DNA (eDNA) technologies.

Regional Councils support and are often involved in partnerships with other agencies and groups proactively engaging mitigation efforts and research into remediating environmental damage and expected responses. One example is the Whatawhata Integrated Catchment Management (ICM) project in the Horizons region, which is the longest continuously monitored before and after control impact catchment scale study (since 1995) in New Zealand, tracking responses in stream ecosystem health and water quality[46]. A compilation of work to improve the health of estuaries (mountains to the sea) is provided by DOC as an interactive map with links to agency and community initiatives, strategic plans, plant lists and restoration guides[22]. Most Regional Councils have riparian management programmes and plans in place for landowners to achieve water quality and biodiversity outcomes by excluding livestock and planting natural vegetation.

C2-(ii). Central government driven

Central government actions have primarily arisen from Resource Management Act (RMA) environmental regulations and national policy statements produced by MfE for freshwater management (NPS-FM2020[70]) and DOC for coastal (NCPS2010[17]). Regional Councils, with communities and tangata whenua develop their plans and manage their regions from these policy statements. The National Objectives Framework (NOF) in the NPS-FM2020 sets out the process which requires identifying freshwater values and attributes, target states and monitoring and reporting requirements. The NPS-FM applies to receiving environments, such as estuaries and coastal waters where they are connected and affected by freshwater inputs. The stipulated response to degradation in an attribute (e.g., lake phytoplankton trophic state/ Chl.*a*) is to take action to halt or reverse the change, by making or changing a regional plan or preparing an action plan which must identify the deterioration cause, methods to address and evaluation of effectiveness. However, since the 1940's the science-policy interface has often functioned poorly in the face of continued environmental degradation, and this led to five imperatives for implementing the relatively new NPS-FM 2020: (1) inclusiveness, (2) partnership with Māori, (3) strategic planning, (4) funding mandate, and (5) authorising agency[55]. There are real challenges and opportunities ahead in the values, state, trends, and human impacts on New Zealand's freshwaters[39]. However, the demonstration of the cost effectiveness and benefits of a national riparian restoration programme in New Zealand[14], suggests that a pathway could be found toward effective improvements in trophic states (Chl.*a*) in both freshwater and marine receiving environments.

There is no direct funding from central government for environmental monitoring. MBIE has a range of investment funds that support scientific research effort and infrastructure directly impacting our state of the environment, knowledge, impacts of environmental stressors, mitigation opportunities and management levers. Non-contestable funding (Strategic Science Investment Fund, SSIF) provides long-term funding to research providers and some of this SSIF funding has supported long-term environmental monitoring and research. With the decline of SSIF funding in real terms, much of the long-term environmental time-series is under threat.

The National Science Challenges (2016-2026) advanced some specific objectives, projects, and tools applicable to improving water quality and providing management insight. Our Land and Water[65] has the Healthy Estuaries | Ki Uta Ki Tai programme to assess the interaction between loadings of different contaminant from freshwaters on the health and functioning of estuaries. Mapping of Freshwater Contaminants programme has a series of projects to classify landscapes and management practices according to their contaminant delivery from source to sink. The Monitoring Freshwater Improvement Actions programme is monitoring and effectiveness of interventions and mitigation actions and the development of a WebApp. Sustainable Seas[66] also has several relevant programmes such as Degradation and Recovery (assessing cumulative effects caused by human activities and potential for recovery), and a range of ecosystem-based management (EBM) approaches: improving decision making (embedded in marine management and governance), enhance practices (tailoring practice, policy, regulation, and legislation), and in action (real world trials with stakeholders and Māori). With the NSC coming to an end, and no replacement, advances in understanding and time-series observation of estuarine/coastal Chl.*a* is likely to slow.

C2-(iii). Iwi/hapū driven

Many of the programmes mentioned above in National Science Challenges have strong collaboration with iwi and hapū Māori. Specifically, in Sustainable Seas the "Empowering Mana Moana" programme focussed on marine management and governance; in Our Land and Water included a component “Matarau: Empowering Māori Landowners in Land Use Decisions”. The DOC “Monitoring estuaries map”[20] and “Restoring estuaries map”[20], also illustrate historical and active hapū and iwi efforts with relevance to improving water quality and estuarine health. One example is the Omarumutu Marae Papakainga and Waiaua Estuarine Restoration Project[81].

C2-(iv). NGO, community driven

The DOC “Monitoring estuaries map”[20] and “Restoring estuaries map”[20], documents a range of historical and active community driven effort with relevance to improving water quality and estuarine health. One example is the Friends of Mangemangeroa, a community group restoring native vegetation in the valley in river catchment to improve water quality entering the estuary [64]. Fonterra also have a range of sustainable catchment projects around the country with various central and region government agencies, iwi, scientists, and other primary sector organisations with the national movement on catchment restoration[29].

C2-(v). Internationally driven

There are a range of indirect interventions and international mechanisms relevant to monitoring, understanding and managing factors affecting Chl.*a* in estuaries and coastal water surrounding New Zealand. The Ministry of Foreign Affairs and Trade (MFAT) serves as New Zealand's representative in global discussions and the implementation of international agreements concerning marine governance and fisheries management[69] (which are affected by changes to Chl.*a*). Notably, MFAT plays a key role in upholding agreements such as: The UN Convention on the Law of the Sea (UNCLOS), which governs activities within New Zealand's Exclusive Economic Zone (EEZ) and continental shelf; Marine biological diversity beyond national jurisdiction (high seas); Ocean Acidification and its impacts.

New Zealand is a signatory to the United Nations 2030 Agenda for Sustainable Development Goal 6, which specifically addresses clean water and sanitation[108]. While it does not provide a direct legal obligation to New Zealand, it reflects the countries' commitment to ensuring access to clean water and improving water quality.

New Zealand is also a party to the Ramsar Convention on Wetlands[90]. The Convention aims to conserve and sustainably use wetlands, including freshwater and estuarine ecosystems. There are several designated several Ramsar sites, which are internationally recognized wetlands of importance (Farewell Spit, Firth of Thames, Kopuatai Peat Dome, Manawatu Estuary, Awarua Waituna Lagoon, Wairarapa-Moana, and Whagamarino wetland) [21].

Part D—Impact analysis

D1. What would be the environmental/human health impacts of not managing this attribute?

Unmanaged eutrophic Chl.*a* in estuarine and coastal waters can lead to harmful algal blooms, oxygen depletion, and degraded water quality, posing risks to aquatic ecosystems, human health, and Māori cultural practices.

D2. Where and on who would the economic impacts likely be felt? (e.g., Horticulture in Hawke's Bay, Electricity generation, Housing availability and supply in Auckland)

Negative economic impacts of eutrophic states of Chl.*a* in estuarine and coastal waters can arise due to adverse effects on: (1) tourism; (2) coastal/inshore wild-caught fisheries (finfish and shellfish; commercial, recreational and cultural fisheries); (3) aquaculture; and (4) water-based recreational industries in coastal regions. Immediate effects include tourism declines and aquaculture and fisheries closures, particularly due to algal blooms. Longer-term implications may involve shifts in higher trophic organisms (e.g., foraging birds, fish, and migrating species such as sharks, dolphins, and whales), tourism patterns and changes in aquaculture practices, requiring ongoing monitoring and research for mitigation.

D3. How will this attribute be affected by climate change? What will that require in terms of management response to mitigate this?

Climate change is likely to significantly impact trophic state and Chl.*a* in estuarine and coastal systems waters [89]. Warmer temperatures will likely stimulate algal growth by increasing the metabolic rates of phytoplankton, but effects of climate change will also be felt through a range of other processes. Alterations in nutrient cycling patterns will occur from increased rainfall and runoff, leading to the transportation of higher amounts of nutrients like nitrogen and phosphorus into water bodies. Additionally, changes in water temperature, wind, waves and precipitation will alter vertical stratification (water-column structure) and changes to mixed layer depths which affect nutrient availability and light availability, with effects on primary production and Chl.*a*. In extreme cases these will lead to reduce water quality, clarity, HABs, modification of habitat and loss of natural resources, and periods of oxygen depletion (hypoxia). Climate change will also affect zooplankton grazers of phytoplankton and microbial processes, thereby affecting loss rates and export of algal carbon to depth.

In summary, Chl.a in New Zealand estuaries and coastal waters are likely to be sensitive to the effects of climate change, and yet the processes involved are complex, overlapping, poorly-observed or understood, and variable in time and space[12,57]. Climate change drivers of changes in Chl.*a* will act in addition to changes arising from land-use, hydrological and coastal development.

Global moves towards zero carbon dioxide emission and potentially carbon dioxide removal (CDR) strategies would help slow (and potentially reverse) global climate change. In the meantime, management options for Chl.a in estuarine and coastal systems are related to measures aimed at enhancing catchment resilience by addressing land-use practices, landscape management, and hydrological processes[82]. Reforestation, particularly in low-land areas, implementation of riparian buffers, and enhancement and protection of wetlands will help to reduce soil erosion, nutrient runoff, and sedimentation into coastal water bodies. Additionally, enhancing soil health through practices like conservation agriculture and cover cropping can improve water retention and reduce the leaching of nutrients and contaminants into streams and estuaries[95].

References:

[1] Anzecc and Armcanz (2000). "Australian and New Zealand guidelines for fresh and marine water quality." Australian and New Zealand Environment and Conservation Council and Agriculture and Resource Management Council of Australia and New Zealand, Canberra 1: 1-314.

[2] Ataria, J., et al. (2018). "Whakamanahia Te mātauranga o te Māori: empowering Māori knowledge to support Aotearoa's aquatic biological heritage." New Zealand journal of marine and freshwater research 52(4): 467-486.

[3] Aurin, D., et al. (2013). "Spatially resolving ocean color and sediment dispersion in river plumes, coastal systems, and continental shelf waters." Remote Sensing of Environment 137: 212-225.

[4] Behrenfeld, M. J. and P. G. Falkowski (1997). "Photosynthetic rates derived from satellite-based chlorophyll concentrations." Limnology and oceanography 42(1): 1-20.

[5] Blaustein, R. (2015). "Predicting tipping points." World Policy Journal 32(1): 32-41.

[6] Blondeau-Patissier, D., et al. (2014). "A review of ocean color remote sensing methods and statistical techniques for the detection, mapping and analysis of phytoplankton blooms in coastal and open oceans." Progress in Oceanography 123: 123-144.

[7] Brown, A. R., et al. (2020). "Assessing risks and mitigating impacts of harmful algal blooms on mariculture and marine fisheries." Reviews in Aquaculture 12(3): 1663-1688.

[8] Burns, N., et al. (2000). "Protocol for monitoring trophic levels of New Zealand lakes and reservoirs. MfE publication."

[9] Carlson, R. E. (1977). "A trophic state index for lakes." Limnology and oceanography 22(2): 361-369.

[10] Cloern, J. (1996). "Phytoplankton bloom dynamics in coastal ecosystems: a review with some general lessons from sustained investigation of San Francisco Bay, California." Reviews of Geophysics 34(2): 127-168.

[11] Cloern, J. E., et al. (2014). "Phytoplankton primary production in the world's estuarine-coastal ecosystems." Biogeosciences 11(9): 2477-2501.

[12] Collins, D. B. (2020). "New Zealand River Hydrology under Late 21st Century Climate Change." Water 12(8): 2175.

[13] Cruz, R. C., et al. (2021). "A review of recent machine learning advances for forecasting harmful algal blooms and shellfish contamination." Journal of Marine Science and Engineering 9(3): 283.

[14] Daigneault, A. J., et al. (2017). "A national riparian restoration programme in New Zealand: Is it value for money?" Journal of Environmental Management 187: 166-177.

[15] Davies-Colley, R. J., et al. (1997). "Matching natural water colors to Munsell standards." Journal of the American Water Resources Association 33(6): 1351-1361.

[16]Dickey, T., et al. (2006). "Optical oceanography: recent advances and future directions using global remote sensing and in situ observations." Reviews of Geophysics 44(1): 1-39.

[17]DOC (2010). New Zealand coastal policy statement 2010. DOC. Wellington, DOC.

[18]DOC (2022). Marine Monitoring and Reporting Framework. DOC. Wellington, Department Of Conservation: 224.

[19]DOC (2024). "Estuaries spatial database." from https://www.doc.govt.nz/nature/habitats/estuaries/estuaries-spatial-database/.

[20]DOC (2024). "Monitoring estuaries map." from https://www.doc.govt.nz/nature/habitats/estuaries/monitoring-estuaries-map/.

[21]DOC (2024). "Ramsar Convention on Wetlands." from https://www.doc.govt.nz/about-us/international-agreements/ecosystems/ramsar-convention-on-wetlands/#:~:text=New%20Zealand%20has%20listed%20seven%20sites%20covering%20almost,Estuary%2C%20Manawatu%20Wairarapa%20Moana%2C%20Wairarapa%20Farewell%20Spit%2C%20Nelson

[22]DOC (2024). "Restoring estuaries map." from https://www.doc.govt.nz/nature/habitats/estuaries/restoring-estuaries-map/.

[23]Dudley, B., et al. (2018). "New Zealand Coastal Water Quality Assessment": Prepared for Ministry for the Environment." NIWA Client Report(2016093CH).

[24]Dudley, B. D., et al. (2020). "Effects of agricultural and urban land cover on New Zealand's estuarine water quality." New Zealand journal of marine and freshwater research 54(3): 372-392.

[25]Elvines, D., et al. (2019). Best management practice guidelines for salmon farms in the Marlborough Sounds: Part 2: Water quality standards and monitoring protocol (Version 1.0), Ministry for Primary Industries.

[26]Falkowski, P. G. and J. A. Raven (1997). Aquatic Photosynthesis. Massachusetts, Blackwell Science, Inc.

[27]Fisher, C. (2023). State and trends for water quality in rivers, lakes, coastal and estuary sites in the Manawatū-Whanagnui Region: For the period ending 30 June 2022, Horizons Regional Council: 141.

[28]Foley, M. M., et al. (2018). Marine water quality state and trends in the Auckland region from 2007 to 2016, Auckland Council, Te Kaunihera o Tāmaki Makaurau Auckland, New Zealand.

[29]Fonterra (2024). "Working to protect and regenerate nature." from https://www.fonterra.com/nz/en/sustainability/planet/nature.html.

[30]Forrest, B., et al. (2007). "Review of the ecological effects of marine finfish aquaculture: final report." Prepared for Ministry of Fisheries. Cawthron Rep 1285: 71.

[31]Fraser, C., et al. (2021). New Zealand coastal water quality assessment 2021. NIWA Client Report, Ministry for the Environment: 49.

[32]Gall, M. and N. Broekhuizen (2023, 01-June-2023). "NIWA-SCENZ satellite water quality analysis of the Pelorus and Queen Charlotte Sounds region." R Notebook. from https://oneniwa.atlassian.net/wiki/pages/resumedraft.action?draftId=119341394&draftShareId=9a748a7f-2631-4f46-9eaf-ec4be4e719fe.

[33]Gall, M. and M. Pinkerton (2022). Satellite water quality observations in the South Taranaki Bight: Seasonal patterns and trends NIWA Client Report: WQZ22301. Wellington, NIWA: 65.

[34]Gall, M., et al. (2024). Satellite remote sensing of coastal water quality in New Zealand: The NIWA-SCENZ initiative for state of the environment monitoring. AMSA-NZMSS 2024: Navigating uncertainty for a future sustainable ocean, Hobart.

[35]Gall, M., et al. (2019). "Predicting visual clarity and light penetration from water quality measures in New Zealand estuaries." Estuarine, Coastal and Shelf Science 219: 429-443.

[36]Gall, M., et al. (2024). "Vertical stratification of phytoplankton biomass in a deep estuary site: implications for satellite-based net primary productivity." Frontiers in Marine Science 10:1250322.

[37]Gall, M. P., et al. (2022). "Satellite remote sensing of coastal water quality in New Zealand." New Zealand journal of marine and freshwater research 56(3): 585-616.

[38]Giles, H., et al. (2021). "Best practice guidelines for benthic and water quality monitoring of open ocean finfish culture in New Zealand."

[39]Gluckman, P., et al. (2017). "New Zealand's fresh waters: values, state, trends and human impacts."

[40]Gobler, C. J. (2020). "Climate change and harmful algal blooms: insights and perspective." Harmful Algae 91: 101731.

[41]Gordon, H. R. (1988). "Semianalytic radiance model of ocean color." Journal of Geophysical Research, Wash., D.C 93(D9): 10909-10924.

[42]Hale, R., et al. (2024). "Hindcasting estuary ecological states using sediment cores, modelled historic nutrient loads, and a Bayesian network." Frontiers in Marine Science 11: 1374869.

[43]Hallegraeff, G. M., et al. (2021). "Overview of Australian and New Zealand harmful algal species occurrences and their societal impacts in the period 1985 to 2018, including a compilation of historic records." Harmful Algae 102: 101848.

[44]Henson, S. A., et al. (2010). "Detection of anthropogenic climate change in satellite records of ocean chlorophyll and productivity." Biogeosciences 7(2): 621-640.

[45]Hill, P. R., et al. (2020). "HABNet: Machine learning, remote sensing-based detection of harmful algal blooms." IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing 13: 3229-3239.

[46] Hughes, A. (2024). "The Whatawhata Integrated Catchment Management Project." Freshwater. from https://niwa.co.nz/freshwater/whatawhata-integrated-catchment-management-project.

[47] Hume, T., et al. (2016). A classification of New Zealand's coastal hydrosystems. NIWA Client Report 120 pp.

[48] Ingley, R. and J. Groom "Coastal and Estuarine Water Quality in Tāmaki Makaurau/Auckland: 2020 Annual Data Report."

[49] IOCCG (2000). Remote sensing of ocean colour in coastal, and other optically-complex, waters. Reports of the International Ocean-Colour Coordinating Group. S. Sathyendranath. Dartmouth, Canada, IOCCG. IOCCG Report Series, No. 3: 140.

[50] IOCCG (2018). Earth observations in support of global water quality monitoring. Reports and Monographs of the International Ocean Colour Coordinating Group. S. Greb, A. Dekker and C. Binding. Dartmouth, Canada, IOCCG. IOCCG Report Series, No. 17: 125.

[51] Keeley, N., et al. (2009). Review of the ecological effects of farming shellfish and other non-finfish species in New Zealand, Cawthron Report.

[52] Kirk, J. T. O. (2011). Light and photosynthesis in aquatic ecosystems. Cambridge, Cambridge University Press.

[53] Kitsiou, D. and M. Karydis (2011). "Coastal marine eutrophication assessment: a review on data analysis." Environment international 37(4): 778-801.

[54] Larned, S., et al. (2016). "Water quality in New Zealand rivers: current state and trends." New Zealand journal of marine and freshwater research 50(3): 389-417.

[55] Larned, S. T., et al. (2022). "Freshwater science–policy interactions in Aotearoa-New Zealand: lessons from the past and recommendations for the future." Australasian Journal of Water Resources 26(1): 131-152.

[56] Larned, S. T., et al. (2020). "Evidence for the effects of land use on freshwater ecosystems in New Zealand." New Zealand journal of marine and freshwater research 54(3): 551-591.

[57] Law, C. S., et al. (2018). "Climate change projections for the surface ocean around New Zealand." New Zealand journal of marine and freshwater research 52(3): 309-335.

[58] LAWA (2023). "Land Air Water Aotearoa: Estuary Health." from https://www.lawa.org.nz/explore-data/estuaries#/tb-national.

[59] Leduc, D., et al. (2023). "Cyclone impacts on fisheries." New Zealand Aquatic Environment and Biodiversity: 177.

[60] Lee, Z. P., et al. (2002). "Deriving inherent optical properties from water color: a multiband quasi-analytical algorithm for optically deep waters." Applied optics 41(27): 5755-5772.

[61] Lee, Z. P., et al. (2009). "An update of the quasi-analytical algorithm (QAA_v5)." International Ocean Color Group Software Report.

[62] Lehmann, M. K., et al. (2018). "Colour Classification of 1486 Lakes across a Wide Range of Optical Water Types." Remote Sensing 10(8): 1273.

[63] Lyver, P. O. B., et al. (2015). "Looking back for the future: local knowledge and palaeoecology inform biocultural restoration of coastal ecosystems in New Zealand." Human Ecology 43: 681-695.

[64] Mangemangeroa (2024). "Friends of Mangemangeroa." from https://mangemangeroa.org.nz/.

[65] MBIE (2024). "National Science Challenge: Our Land and Water | Toitū te Whenua, Toiora te Wai." from https://ourlandandwater.nz/.

[66] MBIE (2024). "National Science Challenge: Sustainable Seas | Ko ngā moana whakauka." from https://www.sustainableseaschallenge.co.nz/.

[67] McBride, G. B. (2019). "Has Water Quality Improved or Been Maintained? A Quantitative Assessment Procedure." J Environ Qual 48(2): 412-420.

[68] McKindsey, C. W., et al. (2006). "Review of recent carrying capacity models for bivalve culture and recommendations for research and management." Aquaculture 261(2): 451-462.

[69] MFAT (2024). "Oceans and Fisheries." from https://www.mfat.govt.nz/en/environment/oceans-and-fisheries.

[70] MfE (2024). National policy statement for freshwater management 2020: January 2024, Ministry for the Environment: 70.

[71] MfE and StatsNZ (2022). Our marine environment 2022. New Zealand's Environmental Reporting Series.

[72] Milne, J., et al. (2018). National Environmental Monitoring Standard for discrete Water Quality Sampling and Testing. Vol. 1, Groundwater. Vol. 2, Rivers. Vol. 3, Lakes. Vol. 4, Coastal., Ministry for the Environment, Wellington.

[73] Morel, A., et al. (1996). "Measured and modeled primary production in the northeast Atlantic (EUMELI JGOFS program): the impact of natural variations in photosynthetic parameters on model predictive skill." Deep Sea Research Part I: Oceanographic Research Papers 43(8): 1273-1304.

[74] NIWA-SCENZ (2024). "Trendy-SCENZ." from https://gis.niwa.co.nz/portal/apps/experiencebuilder/template/?id=9794f29cd417493894df99d422c30ec2&page=Projects.

[75] NIWA (2024). "Ngā Waihotanga Iho - The Estuary Monitoring Toolkit." from https://niwa.co.nz/coasts/estuaries/nga-waihotanga-iho-estuary-monitoring-toolkit.

[76]Nixon, S. W. (1995). "Coastal marine eutrophication: a definition, social causes, and future concerns." Ophelia 41(1): 199-219.

[77]NZCPS (2010). New Zealand Cosatal Policy Statement 2010. Department of Conservation.

[78]O'Reilly, J., et al. (1998). "Ocean color chlorophyll algorithms for SeaWiFS." Journal of geophysical Research 103(C11): 24937-24953.

[79]Oliver, M. (2014). "Coastal State of the Environment monitoring programme."

[80]Oliver, M. D. and J. R. Milne (2012). Coastal water quality and ecology in the Wellington region: State and trends, Greater Wellington Regional Council.

[81]Omaramutu (2024). Omarumutu Papakainga Restoration & Waiaua estuarine project.

[82]Palmer, M. A., et al. (2009). "Climate change and river ecosystems: protection and adaptation options." Environmental management 44: 1053-1068.

[83]Petit, F., et al. (2022). "Influence of the phytoplankton community composition on the in situ fluorescence signal: Implication for an improved estimation of the chlorophyll-a concentration from BioGeoChemical-Argo profiling floats." Frontiers in Marine Science 9: 959131.

[84]Pinkerton, M., et al. (2023). Monitoring ocean health: 2023 update on satellite indicators for surface temperature, productivity and suspended solids. NIWA Client Report: WN2023217. Wellington, NIWA.

[85]Pinkerton, M., et al. (2021). "NIWA Seas, Coasts and Estuaries New Zealand (NIWA-SCENZ). Image services of satellite water quality products for coastal New Zealand." NIWA-Wellington. from https://data-niwa.opendata.arcgis.com/datasets/niwa-scenz-ocean-colour-application.

[86]Pinkerton, M., et al. (2019). "Satellite indicators of phytoplankton and ocean surface temperature for New Zealand." Wellington: Ministry for the Environment.

[87]Pinkerton, M. H., et al. (2015). Reporting on the state of the New Zealand marine environment: recommendations for ocean indicators as part of the Atmospheric and Ocean Climate Change Tier 1 Statistic, Ministry for Primary Industries.

[88]Plew, D. R., et al. (2020). "Assessing the eutrophic susceptibility of New Zealand estuaries." Estuaries and Coasts 43(8): 2015-2033.

[89]Rabalais, N. N., et al. (2009). "Global change and eutrophication of coastal waters." ICES Journal of Marine Science 66(7): 1528-1537.

[90]RAMSAR (2024). "The Convention on Wetlands." from https://www.ramsar.org/.

[91]Rickard, G. and A. Swales (2009). Nga Waihotanga Iho – the Estuary

[92] Robertson, B., et al. (2016). "NZ estuary trophic index screening tool 1." Determining eutrophication susceptibility using physical and nutrient load data. Prepared for Environlink tools project: Estuarine trophic index 47: 0-1.

[93] Rolton, A., et al. (2022). "Effects of harmful algal blooms on fish and shellfish species: A case study of New Zealand in a changing environment." Toxins 14(5): 341.

[94] Safi, K., et al. (2022). "Microplankton Interactions with Decadal-Scale Nutrient Enrichment in a Deep Estuary, with Implications for Eutrophication-Related Ecosystem Stressors." Estuaries and Coasts 45(8): 2472-2491.

[95] Sahu, G., et al. (2020). "Conservation agriculture-a way to improve soil health."

[96] Scarsbrook, M. and A. Melland (2015). "Dairying and water-quality issues in Australia and New Zealand." Animal Production Science 55(7): 856-868.

[97] Smith, V. H. (2003). "Eutrophication of freshwater and coastal marine ecosystems a global problem." Environmental Science and Pollution Research 10: 126-139.

[98] Snelder, T. H. and B. J. F. Biggs (2002). "Multiscale river environment classification for water resources management." Journal of the American Water Resources Association 38(5): 1225-1239.

[99] Snelder, T. H., et al. (2007). "Development of an ecologic marine classification in the New Zealand region." Environmental management 39: 12-29.

[100] Snelder, T. H., et al. (2020). "Nitrogen loads to New Zealand aquatic receiving environments: comparison with regulatory criteria." New Zealand journal of marine and freshwater research 54(3): 527-550.

[101] StatsNZ (2022). "Coastal and estuarine water quality." from https://www.stats.govt.nz/indicators/coastal-and-estuarine-water-quality.

[102] StatsNZ (2022). "Latest trends for coastal and estuarine water quality." from https://www.stats.govt.nz/news/latest-trends-for-coastal-and-estuarine-water-quality/.

[103] Stenton-Dozey, J. M., et al. (2021). "New Zealand aquaculture industry: research, opportunities and constraints for integrative multitrophic farming." New Zealand journal of marine and freshwater research 55(2): 265-285.

[104] Stevens, C. L., et al. (2019). "Physical oceanography of New Zealand/Aotearoa shelf seas–a review." New Zealand journal of marine and freshwater research 55(1): 6-45.

[105] Swales, A., et al. (2011). Ngā Waihotanga Iho : : estuary monitoring toolkit for iwi. Wellington, New Zealand :, NIWA.

[106] Tadaki, M. (2022). Freshwater monitoring: Challenges and needs of Regional Councils, Cawthron. Grant 2218-NLRC230: 62.

[107] Townsend, M., et al. (2014). "Overcoming the challenges of data scarcity in mapping marine ecosystem service potential." Ecosystem Services 8: 44-55.

[108] UN (2024). "Goal 6: Ensure availability and sustainable management of water and sanitation for all." from https://sdgs.un.org/goals/goal6.

[109] Van der Woerd, H. J. and M. R. Wernand (2018). "Hue-angle product for low to medium spatial resolution optical satellite sensors." Remote Sensing 10(2): 180.

[110] Vandermeulen, R., et al. (2020). "150 shades of green: Using the full spectrum of remote sensing reflectance to elucidate color shifts in the ocean." Remote Sensing of Environment 247: 111900.

[111] Wang, S., et al. (2018). "Trophic state assessment of global inland waters using a MODIS-derived Forel-Ule index." Remote Sensing of Environment 217: 444-460.

[112] Weeks, E. S., et al. (2013). "Estimating patterns of vulnerability in a changing landscape: a case study of New Zealand's indigenous grasslands." Environmental conservation 40(1): 84-95.

[113] Wells, M. L., et al. (2020). "Future HAB science: Directions and challenges in a changing climate." Harmful Algae 91: 101632.

[114] West, A. O., et al. (2016). "Optical water quality and human perceptions: a synthesis." Wiley Interdisciplinary Reviews: Water 3(2): 167-180.

[115] Yang, H., et al. (2022). "A review of remote sensing for water quality retrieval: Progress and challenges." Remote Sensing 14(8): 1770.

[116] Zeldis, J. (2022). "The New Zealand Estuary Trophic Index." from https://niwa.co.nz/freshwater/new-zealand-estuary-trophic-index.

[117] Zeldis, J., et al. (2022). "Attributing controlling factors of acidification and hypoxia in a deep, nutrient-enriched estuarine embayment." Frontiers in Marine Science: 2107.

[118] Zeldis, J. and D. Plew (2022). "Predicting and scoring estuary ecological health using a Bayesian Belief Network." Frontiers in Marine Science: 1037.

[119] Zeng, L. and D. Li (2015). "Development of in situ sensors for chlorophyll concentration measurement." Journal of Sensors 2015.

[120] Kainamu, A (2010), The fishery trend and feeding capacity of the New Zealand Littleneck Clam, Austrovenus stutchburyi, in a southern New Zealand inlet. Masters of Science thesis, University of Otago.