

Kelp Forest and Temperate Reef Accounting

Provides guidance on compiling ecosystem accounts for kelp forests and temperate rocky reef ecosystems.

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OUTCOME

This Circular provides guidance on compiling ecosystem accounts for kelp forests and temperate rocky reef ecosystems. These systems are classified as Emerging because methodological development remains less advanced than for tropical marine ecosystems, so guidance should be treated as indicative rather than prescriptive. The extent and condition methods build on [TG-3.1 Asset Accounts](#), and ecosystem services follow [TG-2.4 Ecosystem Goods and Services](#) and [TG-1.9 Valuation](#). For the foundational accounting framework, see [TG-0.1 General Introduction to Ocean Accounts](#). For comparison with other biogenic marine ecosystems, see [TG-6.1 Coral Reef Accounts](#) and [TG-6.3 Seagrass Accounts](#).

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ABOUT THIS CIRCULAR

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DRAFT

1. Outcome

¶1 This Circular provides guidance on compiling ecosystem accounts for kelp forests and temperate rocky reef ecosystems. These systems are classified as Emerging because methodological development remains less advanced than for tropical marine ecosystems, so guidance should be treated as indicative rather than prescriptive. The extent and condition methods build on **TG-3.1 Asset Accounts**, and ecosystem services follow **TG-2.4 Ecosystem Goods and Services** and **TG-1.9 Valuation**. For the foundational accounting framework, see **TG-0.1 General Introduction to Ocean Accounts**. For comparison with other biogenic marine ecosystems, see **TG-6.1 Coral Reef Accounts** and **TG-6.3 Seagrass Accounts**.

Decision use cases

¶1 **Kelp restoration prioritisation:** Extent and condition accounts identify degraded areas suitable for restoration. Condition indicators tracking canopy density, urchin barrens extent, and species richness provide baseline data for restoration site selection and success monitoring. The kelp-to-barren transition dynamics documented in Section 3.1 inform restoration feasibility assessment.

¶2 **Urchin barren remediation:** Condition accounts tracking urchin density and predator abundance support culling and reintroduction decisions. Phase shift dynamics and hysteresis effects are described in Section 3.1.

¶3 **Temperate reef fisheries support:** Extent accounts quantifying reef area and connectivity inform fisheries management plans for reef-associated species (rock lobster, abalone, temperate reef fish). Condition indicators for herbivore biomass and rugosity provide early warning of trophic cascade effects. Integration with **TG-6.7 Fisheries Accounting** enables assessment of habitat-fisheries linkages.

¶4 **Marine protected area effectiveness:** Condition accounts compiled inside and outside MPAs support quantitative evaluation of protection effectiveness, analogous to the approach described in **TG-6.1 Coral Reef Accounts** Section 3.2.

¶5 **Climate change vulnerability assessment:** Temperature anomaly indicators (Section 3.2) and extent change attributable to marine heatwaves (Section 3.1) provide spatially explicit climate impact metrics. For linking biophysical indicators to climate policy frameworks, see **TG-2.1 Biophysical Indicators** Section 3.4.

¶6 ⓘ Framework Position

¶7 This Circular owns the extent, condition, service and asset accounts for **IUCN GET M1.2 kelp forests and M1.6 subtidal rocky reefs**, and the temperate-reef judgements the generic method does not reach: the canopy-density classification threshold that separates the two types, and the kelp-to-urchin-barren phase shift, which is a reclassification rather than a reduction and exhibits hysteresis across accounting periods.

¶8 It cross-refers for the account structure and the reclassification block (**TG-3.1** Section 3.5.1), extent and condition measurement (**TG-4.1**, **TG-4.8**, **TG-4.9**) and indicator derivation (**TG-2.1**).

¶9 Cultural services recorded for Indigenous communities carry the consent and data-governance requirements in **TG-3.6**.

2. Requirements

¶1 This Circular requires familiarity with **TG-0.1 General Introduction to Ocean Accounts** and **TG-3.1 Asset Accounts**. Compilers will also benefit from **TG-4.1 Remote Sensing Data** for subtidal mapping approaches, **TG-2.1 Biophysical Indicators** for condition indicator derivation, and **TG-0.7 Quality Assurance** for uncertainty documentation.

¶2 **Readiness and sequencing.** Whether a country is positioned to compile this account at all – mandate, data architecture, capacity and the order in which to build – is assessed under **TG-0.8 Implementation Readiness Assessment**, and is not restated here.

3. Guidance Material

¶1 Kelp forests and temperate rocky reefs are classified as GET **M1.2** and **M1.6** within the Marine Shelf biome (M1). For the GET realm/biome/EFG hierarchy and the national crosswalk obligation, see **TG-4.1 Remote Sensing and Geospatial Data** Section 3.2.4.¹

3.1 Extent Accounting

¶1 Ecosystem extent accounts record the area of kelp forests and temperate reef ecosystems and changes over accounting periods, following **TG-3.1 Asset Accounts**².

Ecosystem type definitions

¶1 **Kelp forests** (IUCN GET M1.2) are characterised by dense canopies of large brown macroalgae (Order Laminariales)³. Key genera include *Macrocystis* (giant kelp), *Laminaria*, *Ecklonia*, *Lessonia*, and *Eisenia*. Some kelps (notably *Macrocystis*) can grow to over 30 metres in length with growth rates up to 0.5 metres per day⁴. Kelp forests occur on hard rocky substrates in the photic zone, typically to depths of 30 metres⁵, and are limited to temperate and polar waters, absent from warm tropical waters except in upwelling zones off Peru, the Galapagos, Namibia, Oman, and Cape Verde⁶.

¶2 **Subtidal rocky reefs** (IUCN GET M1.6) are characterised by hard minerogenic substrates supporting communities of macroalgae, sessile invertebrates, and associated mobile fauna⁷. Unlike kelp forests, rocky reefs lack dense macroalgal canopies, with algal growth kept in check by herbivory, storm disturbance, and depth-related light limitation⁸.

¶3 For accounting purposes, the boundary between kelp forests and rocky reefs may be dynamic as kelp canopies expand or contract in response to environmental conditions and herbivore populations⁹. Compilers should establish clear canopy density thresholds or classification rules, document them, and record the rationale for any reclassification decisions.

Mapping challenges

¶1 **Subtidal location.** Subtidal kelp and rocky reef habitats cannot be directly observed from above the water surface in most conditions, limiting the applicability of conventional aerial and satellite remote sensing¹⁰.

¶2 **Water column effects.** Remote sensing of benthic habitats requires correction for water column effects, which adds uncertainty to extent estimates¹¹. The SEEA EA notes that marine ecosystems extend “throughout the water column and include the underlying sediment and seabed”¹². The resulting three-dimensional complexity may not be fully captured by area-based extent measures.

¶3 **Canopy structure variability.** Some kelps form floating surface canopies (e.g., *Macrocystis*), whilst others have subsurface canopies (e.g., *Laminaria*, *Ecklonia*), requiring different detection approaches¹³.

¶4 **Seasonal dynamics.** Kelp biomass can vary substantially across seasons. To address this in annual accounting, compilers should standardise the observation period (for example, recording extent at the late summer maximum) or apply multi-temporal averaging. The chosen approach must be documented and held constant across accounting periods (see Step 2.4)¹⁴.

Recommended approaches

¶1 **Tier 1 (basic):** Use existing global or regional habitat maps (e.g., UNEP-WCMC Ocean Data Viewer or national marine habitat mapping programmes)¹⁵.

¶2 **Tier 2 (intermediate):** Combine satellite remote sensing of surface-canopy kelp with acoustic surveys or diver transects for subsurface habitats. For remote sensing data acquisition and processing, see **TG-4.1 Remote Sensing Data**¹⁶.

¶3 **Tier 3 (advanced):** Develop high-resolution benthic habitat maps using multibeam sonar, under-water video transects, and species distribution modelling, integrated with satellite time series¹⁷.

Extent account structure

¶1 The extent account structure, including the reclassification row block, is set out in **TG-3.1 Asset Accounts** Section 3.5.1 (Tables 2a and 2b) and is not restated here¹⁸. Compile one column per ecosystem type present – typically kelp forests (M1.2) and subtidal rocky reefs (M1.6), and a third for urchin barrens where the national classification recognises them as a distinct type.

¶2 The reclassification block matters more for kelp than for most ecosystems, because the kelp-to-urchin-barren transition is the dominant form of loss and it is a change of **type**, not a reduction: the area stays in the accounting area. Kelp lost to storm damage where the substrate is exposed but not yet colonised is the opposite case and is an unmanaged reduction. A worked illustration of the three available classification approaches is at Box 1 in Section 3.6.

¶3 **Transitions between ecosystem types.** Kelp forests can transition to “urchin barrens” (rocky substrates dominated by sea urchins with minimal macroalgal cover) when herbivore populations increase following predator loss¹⁹. These trophic cascades are ecosystem conversions and should be recorded in extent accounts. Three classification approaches are available (see Box 1 in Section 3.6 for a worked illustration). Compilers should document their chosen approach and its rationale.

Phase shift dynamics

¶1 The kelp-to-urchin-barren transition is characterised by nonlinear dynamics and hysteresis: conditions required to trigger degradation differ from those required for recovery.

State	Dominant Species	Ecosystem Services	Transition Triggers
Kelp-dominated	Kelp canopy	High (habitat, carbon, fisheries)	Urchin increase + warming
Transition	Mixed	Declining	Intermediate grazing pressure
Urchin barren	Urchins on bare rock	Low	Sustained overgrazing

¶2 *Table 2: Kelp-urchin phase shift characteristics*

¶3 Recovery from urchin barrens requires temperature decrease OR urchin removal AND kelp re-seeding. The recovery threshold is higher than the degradation threshold (hysteresis), so reversing the conditions that caused degradation is often insufficient. Phase shifts may result in persistent ecosystem state changes that affect both extent and condition accounts over multiple accounting periods.

3.2 Condition Assessment

¶1 Ecosystem condition accounts record the quality of kelp forest and temperate reef assets using indicators of biotic and abiotic characteristics²⁰. For the general condition accounting methodology, see **TG-3.1 Asset Accounts** Section 3.5.2. For deriving biophysical indicators and connecting them to policy frameworks, see **TG-2.1 Biophysical Indicators**. The measurement protocols for the variables themselves – how each is observed, at what frequency and to what tolerance – are owned

by **TG-4.8 Physical Condition Measurement** and **TG-4.9 Biological Condition Measurement**; this Section selects and interprets them for kelp forests and temperate reefs.

Condition variables

¶1 The SEEA EA identifies six classes of condition characteristics applicable to marine ecosystems²¹. Recommended condition variables for kelp forests and temperate reefs include:

¶2 **Physical and chemical state (A1, A2):**

- ¶3 Sea surface temperature and subsurface temperature profiles
- ¶4 Nutrient concentrations (nitrate, phosphate)
- ¶5 Dissolved oxygen levels
- ¶6 Sedimentation rates

¶7 **Compositional state (B1):**

- ¶8 Kelp species diversity and relative abundance
- ¶9 Abundance of herbivores (particularly sea urchins)
- ¶10 Abundance of apex predators (e.g., sea otters, large fish)
- ¶11 Invasive species presence

¶12 **Structural state (B2):**

- ¶13 Canopy extent and density (for kelp forests)
- ¶14 Urchin barrens extent
- ¶15 Sessile invertebrate cover
- ¶16 Reef structural complexity (rugosity)

¶17 **Functional state (B3):**

- ¶18 Primary productivity
- ¶19 Recruitment of key species
- ¶20 Kelp detritus export

¶21 **Landscape context (C1):**

- ¶22 Connectivity to adjacent ecosystem types
- ¶23 Level of protection (MPA status)

Tiered framework for condition assessment

¶1 **Tier 1 (remote sensing and existing data only):**

- ¶2 Sea surface temperature anomaly (satellite SST)
- ¶3 Surface-canopy kelp extent as a proxy for density (for *Macrocystis* and other surface-canopy species)
- ¶4 Marine protected area coverage (existing GIS layers)

¶5 **Tier 2 (periodic diver and acoustic surveys):**

- ¶6 Kelp canopy density (plants/m² or % cover, diver transects)
- ¶7 Urchin barrens extent (acoustic survey, video)
- ¶8 Species richness (fish and invertebrate counts)
- ¶9 Herbivore abundance

¶10 **Tier 3 (full monitoring programme):**

- ¶11 Reef rugosity index (structure-from-motion photogrammetry, fine-scale bathymetry)
- ¶12 Connectivity metrics from telemetry or genetic data
- ¶13 Functional rates (primary productivity, herbivory rates, recruitment)

¶14 The chosen tier should be documented. For data quality and tiered reporting frameworks, see **TG-0.7 Quality Assurance**.

Climate stressors

¶1 **Ocean warming.** Kelp forests have truncated thermal niches and are sensitive to elevated temperatures²². Marine heatwaves have caused widespread kelp losses, including documented decline of *Ecklonia radiata* forests in Western Australia following the 2011 marine heatwave²³. For the relationship between ecosystem condition and climate-related pressures, see **TG-2.1 Biophysical Indicators**.

¶2 **Ocean acidification.** Reduced pH can affect calcifying organisms such as coralline algae, sea urchins, and shellfish that are integral components of reef communities²⁴.

¶3 **Storm regime changes.** Increased storm intensity can dislodge kelp and create gaps in canopy cover²⁵. Recovery depends on recruitment success and may be impaired if environmental conditions have shifted.

Reference conditions

¶1 Condition indicators should be expressed relative to a reference level representing ecosystem integrity²⁶. Establishing appropriate reference conditions for kelp forests is challenging for three reasons: long-term baselines are often lacking, many systems have been affected by fishing pressure, pollution, and climate change for decades, and natural variability is high. Compilers should document the reference conditions applied and their rationale. Historical reconstructions, minimally impacted reference sites, or modelled baselines may each be appropriate depending on context²⁷.

¶2 Condition accounts should track the area of kelp forests in degraded (barren) versus healthy states, as this provides baseline data for restoration targeting and MPA effectiveness assessment.

3.3 Ecosystem Services

¶1 For the general methodology of ecosystem service measurement and valuation, see **TG-2.4 Ecosystem Goods and Services** and **TG-1.9 Valuation**²⁸.

Provisioning services

¶1 **Wild-harvested products.** Kelp is harvested in some regions for food, fertiliser, animal feed, and industrial products. Sea urchins harvested from rocky reefs are a valuable food product²⁹. These should be recorded as provisioning services with physical flows measured in tonnes and valued at market prices where available.

Regulating services

¶1 **Fisheries habitat.** Kelp forests and rocky reefs provide habitat for commercially important fish and invertebrate species, including rockfish, sea bass, abalone, lobster, and bivalves³⁰. For accounting purposes, this is treated as a habitat or nursery maintenance service (an intermediate service) following the SEEA EA classification³¹. Habitat and nursery services are intermediate services. Their monetary value cannot equal the full resource rent of an associated fishery without an attribution model, and only the share attributable to the habitat (via a habitat dependency coefficient, dose-response function, or similar) should be recorded as the service value³². For the intermediate-versus-final service distinction, see **TG-2.4 Ecosystem Goods and Services**.

¶2 **Carbon sequestration** (emerging). Kelp forests are productive systems with rapid photosynthetic carbon uptake, but long-term carbon sequestration remains uncertain³³. Unlike seagrasses and mangroves, kelps do not accumulate carbon in sediments at the site of growth. Kelp-derived carbon may be consumed by herbivores, exported as drift material to deep sea sediments, or remineralised in the water column. Recent research suggests a substantial proportion may reach the deep ocean where it can be sequestered on long timescales³⁴. However, quantification methods

are not yet standardised, and the SEEA EA requires that only carbon stored long-term (at least several decades) be counted³⁵. IPCC does not currently include kelp in the wetlands supplement for national greenhouse gas inventories. Compilers who include kelp carbon should flag the provisional nature of current methods.

¶3 **Coastal protection.** Kelp canopies can dampen wave energy, but the magnitude of this service is less well documented than for coral reefs or mangroves³⁶. Empirical studies report wave-height reductions of approximately 7–60% depending on species, canopy density, bathymetry, and wave period, but kelp-specific attenuation coefficients are not yet validated for accounting use. Any estimate should be reported at low confidence with an explicit uncertainty range. See Step 6.4 for the methodological approach and **TG-6.1 Coral Reef Accounts** for the analogous coral reef method.

¶4 **Water quality regulation.** Kelp forests take up nutrients from surrounding waters and can help mitigate eutrophication effects in nutrient-enriched coastal areas³⁷.

Cultural services

¶1 **Recreation and tourism.** Kelp forests and temperate reefs are popular destinations for recreational diving and snorkelling³⁸.

¶2 **Scientific and educational value.** Long-term monitoring sites such as those established by the Partnership for Interdisciplinary Studies of Coastal Oceans (PISCO) provide valuable scientific data³⁹.

¶3 **Cultural and spiritual significance.** Where these services are recorded, the consent, attribution and data-governance requirements in **TG-3.6 Traditional Knowledge** apply and are not restated here. Kelp forests and rocky reefs may have cultural significance for coastal Indigenous communities, supporting traditional fishing practices, food security, and cultural identity⁴⁰.

Service quantification challenges

¶1 For Emerging-status ecosystems, quantification faces particular challenges: limited spatial extent data, less-developed ecological production functions, poorly documented beneficiary populations, and fewer monetary valuation studies to support benefit transfer. Compilers should document methods and assumptions, and communicate uncertainty to users. See **TG-0.7 Quality Assurance**.

3.4 Compilation Procedure

¶1 The procedure follows the asset accounting framework from **TG-3.1 Asset Accounts** and data quality protocols from **TG-0.7 Quality Assurance**.

Step 1: Define ecosystem accounting area (EAA)

¶1 Define the spatial boundary of the accounting area, typically aligned with national marine waters or a regional marine planning area. Document the coordinate system, vertical datum for depth measurements, and seaward boundary (territorial sea, EEZ, or other jurisdictional limit).

¶2 **1.1 Spatial disaggregation within the EAA.** Decision use cases in Section 1 (MPA effectiveness, restoration targeting) require accounts at the management unit level (individual MPAs, bioregions, depth bands) as well as the EAA-wide aggregate. Sub-unit accounts must be additive to the national total. Compilers should adopt the MPA comparison approach described in **TG-6.1 Coral Reef Accounts** Section 3.2, noting that kelp distribution is typically patchier than coral reef distribution and sub-unit boundaries should reflect ecological structure where possible.

Step 2: Delineate ecosystem assets

¶1 **2.1 Assemble spatial data layers:**

- ¶2 Bathymetric data (depth)

- ¶3 Substrate classification (rocky vs. soft sediment)
- ¶4 Water quality data (turbidity, nutrient levels)
- ¶5 Existing habitat maps (national, regional, or global datasets)

¶6 **2.2 Apply ecosystem type criteria:**

- ¶7 M1.2 Kelp forests: Rocky substrate + depth 3–30m + kelp canopy present
- ¶8 M1.6 Temperate reefs: Rocky substrate + depth <50m + no kelp canopy or sparse kelp

¶9 **2.3 Map ecosystem extent** using the Tier approach described in Section 3.1.

¶10 **2.4 Address seasonal variation:**

- ¶11 Option A: Standardise observation to late summer (maximum canopy extent)
- ¶12 Option B: Multi-temporal averaging across seasons
- ¶13 Document chosen approach and rationale
- ¶14 **Consistency principle:** The seasonal standardisation method must be held constant across consecutive accounting periods. Switching methods introduces spurious extent changes. If a method change is unavoidable, back-calculate prior period estimates using the new method and document the revision as a methodological break in the time series, following **TG-0.7 Quality Assurance**.

¶15 **2.5 Generate extent account:**

- ¶16 Calculate opening extent (t0) for each ecosystem type
- ¶17 Identify additions, reclassifications, and reductions during accounting period
- ¶18 Calculate closing extent (t1)

Step 3: Select condition variables

¶1 **3.1 Apply SEEA ECT framework:**

- ¶2 Select 1–2 variables per ECT class (A1 physical, A2 chemical, B1 compositional, B2 structural, B3 functional, C1 landscape)
- ¶3 Aim for 6–10 variables total
- ¶4 Prioritise variables with available data and policy relevance
- ¶5 ECT class coding affects how accounts are aggregated and compared internationally. Brief justifications for each class assignment should be documented.

¶6 **3.2 Recommended minimum set (with ECT class justifications):**

- ¶7 **B2: Kelp canopy density (plants/m² or % cover)** – B2 (structural state). Canopy density characterises the physical structure and architectural organisation of the ecosystem (SEEA EA Table 5.1).
- ¶8 **B2: Urchin barrens extent (% of reef area)** – B2 (structural state). Habitat-state coverage metrics measure structural arrangement, not species composition.
- ¶9 **B1: Species richness (fish + invertebrate count)** – B1 (compositional state). Directly measures which species are present.
- ¶10 **A1: Water temperature anomaly (°C above baseline)** – A1 (physical state). Standard abiotic descriptor.
- ¶11 **A2: Dissolved oxygen concentration (ml/L at depth) or nutrient anomaly (% deviation from baseline nitrate)** – A2 (chemical state). Where both are available, dissolved oxygen is preferred as a primary stress indicator because sub-threshold values can trigger rapid kelp degradation independent of temperature.
- ¶12 **B2: Reef rugosity index (structural complexity)** – B2 (structural state). Rugosity quantifies the three-dimensional physical structure of the reef.

- ¶13 **B3: Kelp net primary productivity (t C/ha/yr) or recruitment rate (juvenile sporophytes/m²)** – B3 (functional state). Measures the rate of ecological processes. Recruitment rate is preferred where annual survey data are available, whilst net primary productivity is appropriate for data-rich compilations.
- ¶14 **C1: Connectivity to adjacent kelp patches (habitat fragmentation metric)** – C1 (landscape/seascape context). Characterises the spatial configuration of the ecosystem relative to its surroundings.

¶15 3.3 Data collection methods:

- ¶16 Diver transect surveys for canopy density, species richness, rugosity
- ¶17 Satellite SST data for temperature anomaly
- ¶18 Acoustic surveys and video for urchin barren extent
- ¶19 GIS analysis for connectivity

Step 4: Establish reference conditions

¶1 4.1 Select reference condition approach:

- ¶2 Historical baselines: Pre-1950 or earliest available monitoring data
- ¶3 Contemporary reference sites: Minimally impacted reefs within biogeographic region
- ¶4 Modelled baselines: Species distribution models for pristine conditions
- ¶5 Policy targets: National marine park standards or regional management targets
- ¶6 **Biogeographic calibration is required.** Reference levels (V_good, V_bad) vary substantially across kelp species and regions and must be calibrated to the biogeographic context of the EAA before use.

¶7 4.2 Assign reference levels:

- ¶8 V_good: Value at reference condition (high integrity)
- ¶9 V_bad: Value at degraded/collapsed state
- ¶10 For “normal” (direct-direction) variables (higher values = better condition), V_good > V_bad numerically.
- ¶11 For “inverse” variables (lower values = better condition, e.g., urchin barrens extent, temperature anomaly), V_good < V_bad numerically.

¶12 4.3 Example for kelp canopy density (*Ecklonia radiata*, temperate Australia):

- ¶13 V_good = 14 plants/m² (upper reference for dense canopy)
- ¶14 V_bad = 1 plant/m² (functional threshold below which recruitment fails)

¶15 These values are specific to *Ecklonia radiata* in temperate Australia and should not be applied without recalibration to other species or regions. Indicative reference ranges for other major kelp genera are in Table 3.

Genus / region	Typical reference range	Notes
<i>Ecklonia radiata</i> (temperate Australia)	V_good ~4–14 plants/m ² ; V_bad <1 plant/m ²	Adult density categorised in WA studies as low (<2), medium (2–4), high (>4) thalli/m ² ; values at the upper end (14) represent dense canopy under optimal conditions.
<i>Macrocystis pyrifera</i> (California, Southern Ocean)	V_good ~10–18 stipes/m ² ; commonly reported as stipes/m ² rather than plants/m ²	Each plant produces multiple stipes; frond/stipe density is a better proxy for standing crop than plant counts. Reference condition often operationalised at the surface-canopy biomass level.
<i>Laminaria hyperborea</i> (NE Atlantic / Norway)	V_good ~5–15 plants/m ² at exposed shallow sites	Standing stock in 3–5 m exposed sites approximately 6–16 kg fresh weight/m ² ; values vary with wave exposure, depth, and latitude.

¶16 *Table 3: Indicative reference ranges for kelp canopy density by genus and region. All ranges must be verified against primary literature for the specific biogeographic context before use in accounts.*

¶17 **4.4 Document rationale:**

- ¶18 Cite data sources for reference levels
- ¶19 Explain biogeographic context
- ¶20 Note limitations and uncertainties

Step 5: Derive condition indicators

¶1 **5.1 Apply normalisation formula:**

¶2 Condition variables are normalised using the standard formula defined in **TG-2.1 Biophysical Indicators for Ocean Accounts** Section 3.4.1. For kelp forest and temperate reef ecosystems, the formula uses V_{good} (reference, good condition) and V_{bad} (degraded) as parameter names.

¶3 **Worked calculations (kelp-specific examples):**

¶4 *Normal variable – kelp canopy density* ($V_{good} = 14$, $V_{bad} = 1$, $V = 8.5$): Indicator = $(8.5 - 1) / (14 - 1) = 7.5 / 13 = 0.58$

¶5 *Inverse variable – urchin barrens extent* ($V_{good} = 2\%$, $V_{bad} = 60\%$, $V = 22\%$): Indicator = $(22 - 60) / (2 - 60) = (-38) / (-58) = 0.66$

¶6 Both cases yield values in $[0, 1]$ without sign reversal.

¶7 **5.2 Calculate indicators for each variable:**

- ¶8 Opening indicators (t_0)
- ¶9 Closing indicators (t_1)
- ¶10 Change in indicators

¶11 **5.3 Aggregate to composite index (optional):**

- ¶12 Equal-weighted arithmetic mean across indicators
- ¶13 Or apply ECT-weighted approach if ecological rationale supports differential weighting

Step 6: Quantify ecosystem services

¶1 **6.1 Prioritise measurable services:**

- ¶2 Fisheries habitat (regulating and maintenance; an intermediate service – see Section 3.3)
- ¶3 Recreation and tourism (cultural)
- ¶4 Coastal protection (regulating)
- ¶5 Carbon sequestration (regulating, provisional)

¶6 **6.2 Fisheries habitat:**

- ¶7 Estimate proportion of commercial catch attributable to kelp/reef habitat
- ¶8 Habitat and nursery services are intermediate services. Their monetary value cannot equal the full resource rent of an associated fishery without an explicit attribution model. Apply a habitat dependency coefficient (e.g., 0.4–0.6 for obligate reef species) or dose-response function to isolate the ecosystem contribution from the total resource rent.
- ¶9 Where attribution coefficients are unavailable, report “total resource rent from reef-associated fisheries” with an explicit note that full attribution to the habitat service requires additional modelling. See **TG-2.4 Ecosystem Goods and Services** for the intermediate-versus-final service distinction.
- ¶10 Physical units: tonnes of fish
- ¶11 Monetary units: ecosystem-attributable share of resource rent (catch value minus costs, multiplied by habitat dependency coefficient)

¶12 **6.3 Recreation and tourism:**

- ¶13 Estimate person-visits to kelp/reef diving sites
- ¶14 Apply simulated exchange value or travel cost method
- ¶15 Physical units: person-visits
- ¶16 Monetary units: consumer surplus or expenditure-based value

¶17 **6.4 Coastal protection:**

- ¶18 Identify length of coastline protected by kelp/reef
- ¶19 Estimate wave attenuation capacity (% reduction in wave height)
- ¶20 Apply avoided damage cost method
- ¶21 **Methodological note:** Kelp-specific wave attenuation coefficients are not yet validated for accounting use. Empirical studies report reductions ranging from approximately 7–60% depending on species, canopy density, bathymetry, and wave period. Adopt the analogous method from **TG-6.1 Coral Reef Accounts**, parameterised with the most defensible kelp-specific values available for the biogeographic context. Report any coastal protection estimate at low confidence with an explicit uncertainty range. Where a defensible parameterisation cannot be constructed, flag the service as unquantified.
- ¶22 Physical units: km coastline protected
- ¶23 Monetary units: expected annual damages avoided (low confidence)

¶24 **6.5 Carbon sequestration (provisional):**

- ¶25 Estimate kelp biomass production (t dry weight/ha/year)
- ¶26 Apply export coefficient representing the proportion of kelp-derived carbon reaching depths >200 m, where long-term sequestration is assumed
- ¶27 Convert to CO₂ equivalents
- ¶28 Flag as provisional with high uncertainty, not suitable for national GHG inventory use

Step 7: Value ecosystem assets¶1 **7.1 Project future service flows:**

- ¶2 Assume stable condition: Use current service values for projection
- ¶3 Assume degradation trend: Adjust service values based on condition change rate
- ¶4 Scenario analysis: Model alternative management/climate scenarios

¶5 **7.2 Select discount rate:**

- ¶6 Social discount rate typically 3–5% for ecosystem assets
- ¶7 Document rate selection and sensitivity (see Step 7.4)

¶8 **7.3 Calculate net present value:**

$$\text{Asset value} = \sum (\text{Service value year } t \times \text{Discount factor})$$

¶9 The annuity formulation below applies only under the “stable flows” assumption from Step 7.1. Where service flows are projected to change over the horizon, the year-by-year discounted sum must be used.

¶10 For stable flows over the projection horizon:

$$\text{Asset value} = \text{Annual service value} \times \text{Present value annuity factor}$$

¶11 **Treatment of the provisional carbon sequestration component.** Because kelp carbon sequestration is an emerging-confidence service (Section 3.3), it should not be capitalised into a single baseline asset value. Compilers should either (a) quarantine the carbon sequestration row from the baseline asset valuation, or (b) report two asset value estimates (one including and one excluding the provisional carbon component) and quantify the difference.

¶12 **Biomass stocks within ecosystem versus natural resource asset accounts.** Standing kelp biomass forms part of the ecosystem asset. Harvestable seaweed biomass extracted from the ecosystem falls under natural resource assets within the SEEA Central Framework rather than the SEEA EA ecosystem asset. Compilers should keep these stock dimensions distinct to avoid double-counting. See **TG-3.1 Asset Accounts** for the conceptual boundary.

¶13 **7.4 Present value annuity factor (PVAF) and discount-rate sensitivity:**

¶14 For 25 years at 4%: $PVAF = [1 - (1.04)^{-25}] / 0.04 = 15.62$.

Discount rate	25-year horizon	50-year horizon
1%	22.02	39.20
2%	19.52	31.42
3%	17.41	25.73
4%	15.62	21.48
5%	14.09	18.26

¶15 *Table 4: Present value annuity factors for selected discount rates and projection horizons.*

¶16 Compilers must select a discount rate consistent with national Treasury guidance or SEEA EA recommendations, document the chosen rate, and report at least one sensitivity case (e.g., +/-1% around the central rate).

Step 8: Compile integrated accounts

¶1 **8.1 Extent-condition-services linkage:**

- ¶2 Document how condition affects service capacity
- ¶3 Link condition indicators to service quantification assumptions

¶4 **8.2 Populate account tables:**

- ¶5 Extent account (Table 1 structure)
- ¶6 Condition variable account
- ¶7 Condition indicator account
- ¶8 Ecosystem services flow account
- ¶9 Monetary asset account

¶10 **8.3 Quality assurance:**

- ¶11 Apply quality dimensions: accuracy, completeness, timeliness, coherence
- ¶12 Document data sources, methods, and limitations for each account component
- ¶13 Assign quality ratings per **TG-0.7 Quality Assurance**.

Step 9: Connect to policy indicators

¶1 **9.1 Derive policy-relevant indicators:**

- ¶2 Kelp extent change (% per annum) → MPA effectiveness indicator
- ¶3 Urchin barren extent (%) → Restoration targeting indicator
- ¶4 Composite condition index → Ocean health dashboard
- ¶5 Temperature anomaly trend → Climate vulnerability indicator

¶6 9.2 Link to decision contexts:

- ¶7 Reference decision use cases from Section 1
- ¶8 Provide indicator time series and spatial maps

¶9 For detailed guidance on connecting accounts to policy indicators, see **TG-2.1 Biophysical Indicators** Section 3.3.

3.5 Data and Methods Gaps

¶1 The Emerging status of this Circular reflects gaps in data availability and methodological development.

Extent mapping

¶1 Priority gaps:

- ¶2 Globally consistent mapping of kelp forest extent remains incomplete
- ¶3 Subsurface kelp species are poorly captured by current satellite-based approaches
- ¶4 Temporal coverage is insufficient to distinguish long-term trends from natural variability
- ¶5 Standardised protocols for classifying transitions between kelp forests, rocky reefs, and urchin barrens are lacking

¶6 Development priorities:

- ¶7 Investment in satellite-based monitoring capable of detecting subsurface macroalgae
- ¶8 Integration of acoustic survey methods with remote sensing
- ¶9 Development of change detection algorithms suited to dynamic kelp systems ⁴¹
- ¶10 Engagement with international research networks such as the Kelp Ecosystem Ecology Network (KEEN). The Emerging badge may be revisited if major mapping advances emerge from these initiatives.

Condition assessment

¶1 Priority gaps:

- ¶2 Reference conditions for many kelp and reef systems are poorly established
- ¶3 Monitoring of herbivore (urchin) populations is inconsistent across regions
- ¶4 Climate change impact attribution methods need development

¶5 Development priorities:

- ¶6 Establishment of long-term monitoring programmes in under-represented regions
- ¶7 Development of composite condition indices suited to kelp and reef systems
- ¶8 Improved understanding of phase shift dynamics and early warning indicators ⁴²

Carbon accounting

¶1 Priority gaps:

- ¶2 Fate of kelp-derived carbon remains uncertain
- ¶3 Methods for quantifying carbon export to deep ocean are not standardised
- ¶4 IPCC does not currently include kelp in the wetlands supplement for national greenhouse gas inventories

¶5 Development priorities:

- ¶6 Research to quantify carbon sequestration pathways
- ¶7 Development of accounting protocols that reflect current scientific understanding
- ¶8 Coordination with IPCC and blue carbon initiatives ⁴³

Valuation

¶1 Priority gaps:

- ¶2 Economic valuation studies for kelp and temperate reef services are limited compared to tropical systems
- ¶3 Resource rent estimates for kelp-associated fisheries are rarely compiled
- ¶4 Benefit transfer approaches lack locally calibrated studies

¶5 Development priorities:

- ¶6 Primary valuation studies in the North Pacific, Southern Ocean, and North Atlantic
- ¶7 Integration of kelp forest values into broader natural capital assessments⁴⁴

3.6 Worked Example

¶1 This worked example demonstrates the compilation of kelp forest and temperate reef ecosystem accounts for a hypothetical coastal system in a southern Australian setting. Given the Emerging status of this Circular, methods and values below should be treated as indicative rather than prescriptive.

¶2 **Setting:** A national ecosystem accounting area (EAA) containing 6,500 hectares of kelp forest (M1.2, dominated by *Ecklonia radiata*) and 2,500 hectares of subtidal temperate rocky reef (M1.6), totalling 9,000 hectares.

¶3 Step 1: Extent account (year t to t+1)

Accounting entry	Kelp forests (M1.2)	Subtidal rocky reefs (M1.6)	Total
Opening extent (ha)	6,500	2,500	9,000
Additions to extent			
– Managed expansion (kelp restoration trials)	10	0	10
– Natural expansion (recolonisation)	40	15	55
<i>Total additions</i>	50	15	65
Reclassifications			
– Kelp to urchin barren (M1.2 to M1.6)	-250	+250	0
<i>Net reclassification</i>	-250	+250	0
Reductions in extent			
– Managed reduction (infrastructure, pipelines)	5	5	10
– Natural reduction (marine heatwave, non-reclassified losses)	100	0	100
<i>Total reductions</i>	105	5	110
Net change in extent	-305	+260	-45
Closing extent (ha)	6,195	2,760	8,955

¶4 Note: Net change = Total additions + Net reclassification - Total reductions. For kelp: 50 + (-250) - 105 = -305. For rocky reefs: 15 + 250 - 5 = +260. The 250 hectares of kelp that transitioned to urchin barrens are recorded as a reclassification from M1.2 to M1.6, consistent with the phase shift dynamics in Section 3.1. An additional 100 hectares were lost to marine heatwave damage without transitioning to urchin barrens (recorded as natural reduction).

Box 1: Consequences of the urchin-barren classification choice

Section 3.1 identifies three possible treatments for the 250 ha of kelp that transitioned to urchin barrens. The table below illustrates how each option changes the headline extent figures and kelp extent change rate for the same ecological event.

Option	Treatment of 250 ha	Closing kelp extent (M1.2)	Kelp extent change rate
(a) Reclassify to M1.6 (option used here)	250 ha moves to M1.6 (degraded rocky reef)	6,195 ha	−4.7%
(b) New sub-category M1.6b “Urchin barrens”	250 ha moves to new M1.6b class; baseline M1.6 unchanged	6,195 ha	−4.7% (but barren-specific area visible separately)
(c) Track as condition variable, not extent change	250 ha remains in M1.2 with degraded condition score	6,445 ha	−0.8%

Under options (a) and (b) the headline kelp extent change rate is −4.7%. Under option (c) the same ecological event produces −0.8%, with the 250 ha instead appearing as a decline in the composite condition index. The choice materially changes the headline trend signal and policy interpretation (permanent ecosystem-type loss versus reversible condition degradation). Compilers must document which option they adopt and justify it consistently across accounting periods.

Note on option (b): The 250 ha is allocated to a new sub-category M1.6b (“Urchin barrens”), whilst baseline M1.6 remains at 2,500 ha. The M1.2 closing extent (6,195 ha) and kelp extent-change rate (−4.7%) are identical to option (a). The difference is that option (b) makes the barren-specific area visible as a distinct entry rather than merged into the undifferentiated M1.6 total.

5 Step 2: Condition account

Condition indicators are derived from diver transect surveys and satellite monitoring, using pre-2010 baselines as reference conditions and the normalisation formula from **TG-2.1 Biophysical Indicators for Ocean Accounts** Section 3.4.1 (see also Step 5.1):

Condition variable	Observed value (V)	V_good (reference)	V_bad (degraded)	Indicator score
Kelp canopy density	8.5 plants/m ²	14	1	0.58
Urchin barrens extent (% of reef, inverse)	22%	2%	60%	0.66
Species richness (fish + invertebrate)	48 species	70	15	0.60
Water temperature anomaly (inverse)	+1.2°C above baseline	0°C	+3.0°C	0.60

Note: For inverse variables (urchin barrens extent, temperature anomaly), $V_{\text{good}} < V_{\text{bad}}$ numerically. The unified formula handles both cases without sign reversal. For urchin barrens: $(22 - 60) / (2 - 60) = -38 / -58 = 0.66$.

Composite condition index (equal weights): $(0.58 + 0.66 + 0.60 + 0.60) / 4 = \mathbf{0.61}$

This worked example uses four of the six minimum-set variables recommended in Step 3.2. Rugosity (B2) and connectivity (C1) are excluded for illustrative simplicity. Operational composite indices must cover the full minimum set, and omissions should be justified and documented.

Interpretation: A composite condition index of 0.61 indicates the ecosystem is at 61% of reference condition, reflecting canopy density reduction, expanding urchin barrens, and elevated

water temperatures.

¶11 Step 3: Ecosystem services (annual flows)

Service	Physical quantity	Monetary value (USD)
Fisheries (rock lobster) – total resource rent from reef-associated fishery	180 tonnes	5,400,000 (total resource rent; full habitat-service attribution requires a habitat dependency coefficient – see Step 6.2)
Fisheries (abalone) – total resource rent from reef-associated fishery	95 tonnes	4,750,000 (total resource rent; full habitat-service attribution requires a habitat dependency coefficient – see Step 6.2)
Carbon sequestration (kelp export to depths >200 m)	9,750 t CO ₂ /yr (estimated as 6,195 ha x 0.43 t C/ha/yr export to >200 m x 44/12 CO ₂ /C; provisional, uncertainty range 0.1–0.9 t C/ha/yr; see ³⁴)	780,000 (at USD 80/t CO ₂ ; provisional, not suitable for national GHG inventory use)
Coastal protection (wave attenuation)	40 km coastline (low confidence; wave-attenuation parameterisation per Step 6.4)	2,800,000 (avoided damage, low confidence)
Recreation (diving and snorkelling)	85,000 person-visits	3,400,000 (simulated exchange)
Total valued services (gross)		17,130,000
Total excluding provisional carbon sequestration		16,350,000

¶12 Note: The fisheries values shown are total resource rents of reef-associated fisheries, not the share attributable to the kelp/reef habitat as an intermediate service. The carbon sequestration estimate is provisional and presented with explicit uncertainty so its effect on downstream valuation can be quarantined. The coastal protection figure is reported at low confidence given the wide range of empirical wave-attenuation values for kelp (Step 6.4 and Section 3.3).

¶13 Step 4: Asset valuation

¶14 Applying a 4% social discount rate over a 25-year projection horizon under the stable-flows assumption (Step 7.3) and using PVAF = 15.62 (Step 7.4):

Asset value (including provisional carbon) = 17,130,000 x 15.62 = approximately USD 267,500,000
Asset value (excluding provisional carbon) = 16,350,000 x 15.62 = approximately USD 255,400,000

¶15 The two estimates bracket the influence of the provisional carbon service. The difference (approximately USD 12,200,000, or about 4.6% of gross asset value) is the value the carbon row contributes when capitalised over 25 years at 4%. Compilers should report both figures and avoid embedding the provisional carbon component in a single headline number.

¶16 Sensitivity: PVAF = 15.62 at 4%, 19.52 at 2%, and 22.02 at 1% (Table 4). Applied to the asset value excluding provisional carbon, the sensitivity range spans approximately USD 230 million (at 5%) to USD 360 million (at 1%).

¶17 Policy indicator derivation:

- ¶18 **Kelp extent change rate (combined):** –4.7% for the accounting period (–305 ha / 6,500 ha opening extent: the two components below, offset by +0.8% from 50 ha of additions). This figure must not be used as a trend metric without disaggregation.

- ¶19 *Permanent-loss component*: approximately –1.6% (–105 ha total permanent reduction divided by opening extent). Losses not expected to recover without active management.
 - ¶20 *Phase-shift component*: approximately –3.8% (–250 ha kelp-to-barren reclassification divided by opening extent). Phase-shift area is a candidate for urchin removal and kelp restoration, and should not be interpreted as permanent loss.
 - ¶21 **Urchin barren extent**: 22% of reef area (early warning threshold typically 15–20%).
 - ¶22 **Composite condition index**: 0.61 (moderate condition requiring intervention).
 - ¶23 **Climate stress indicator**: Temperature anomaly +1.2°C (approaching stress threshold).
- ¶24 The disaggregation of the kelp extent change rate is particularly relevant for restoration targeting: the –3.8% phase-shift area is the practical management opportunity, distinct from the –1.6% of permanently lost kelp habitat.

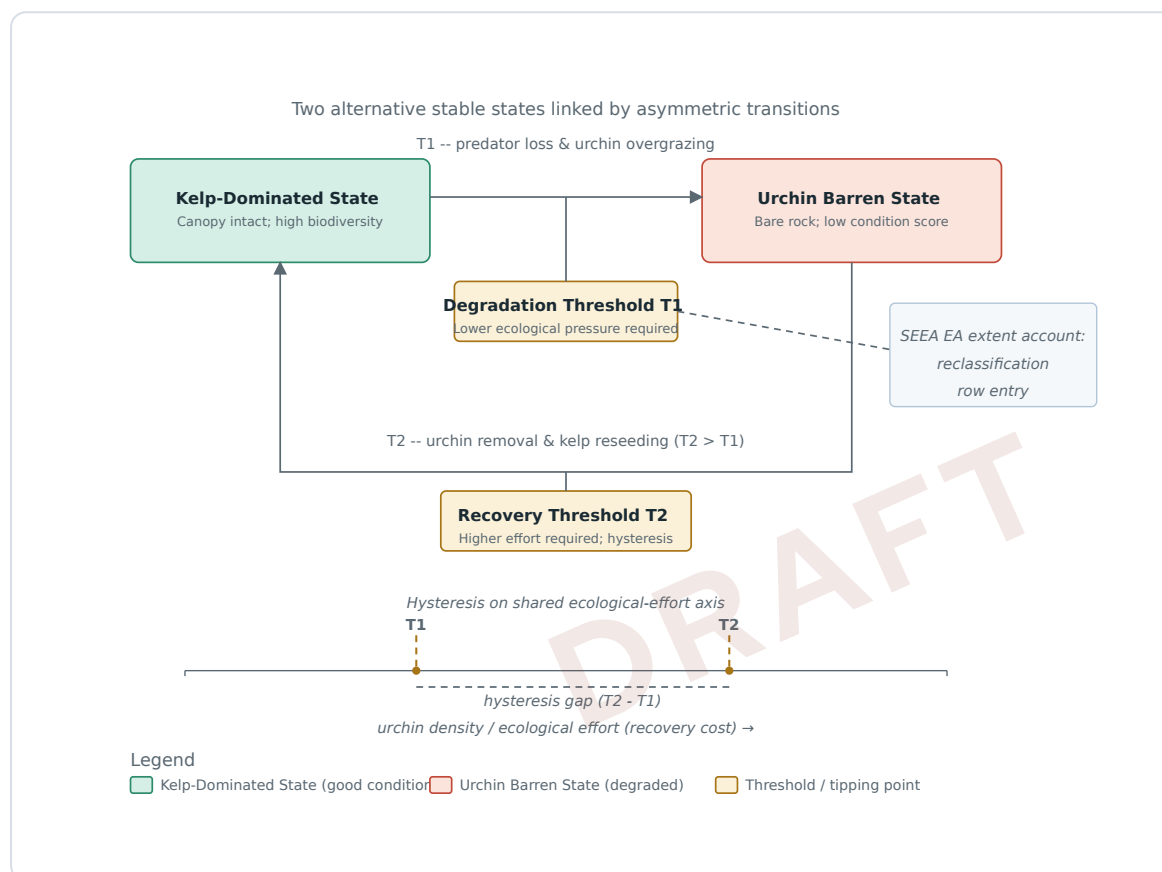


Figure 6.4.1 Kelp-to-urchin-barren phase shift with asymmetric thresholds: recovery (T2) is harder than the forward transition (T1) -- hysteresis. Both transitions write extent-account reclassification and condition-score change rows.

Source: TG-6.4 draft-v7, Section 3.1 (phase-shift dynamics & hysteresis, Table 2) and Box 1 (Section 3.6, classification options for the urchin-barren transition); SEEA EA Table 4.1 (extent account reclassification row); IUCN GET M1.2 (trophic-cascade mechanism).

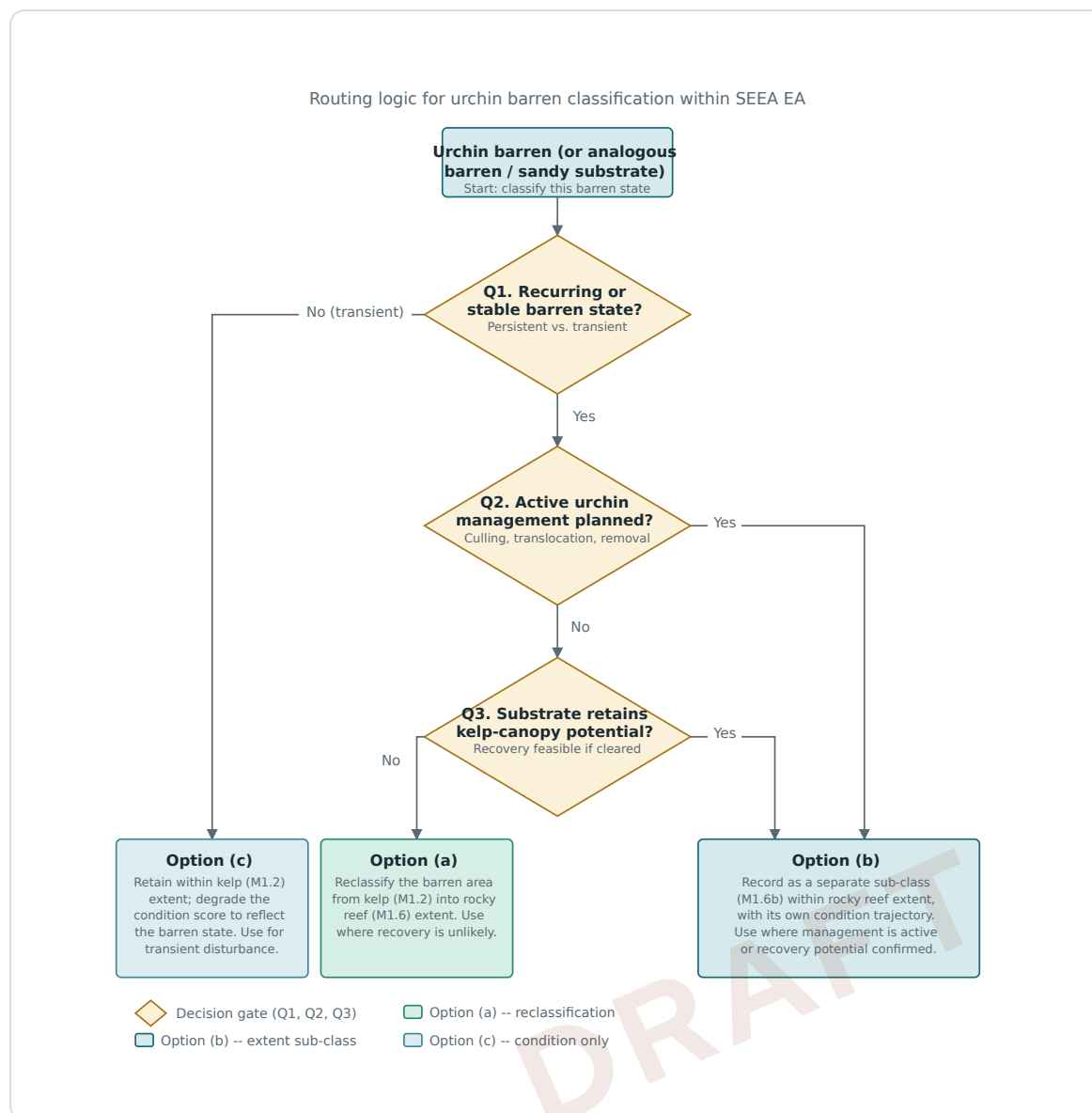


Figure 6.4.2 Three sequential criteria route a kelp area to one of three SEEA EA treatments for urchin barrens (reclassify, sub-class, or condition-only). Option letters match Box 1 (Section 3.6); tree also covers analogous sandy barrens.

Source: TG-6.4 draft-v7, Box 1 (Section 3.6, three options for classifying urchin barrens within national ocean accounts) and Section 3.1 (classification criteria for recurring vs. transient barren states).

4. Acknowledgements

¶1 **Authors:** [To be confirmed]

¶2 **Reviewers:** [To be confirmed]

5. References

- ¶1 IUCN Global Ecosystem Typology (GET), M1 Marine Shelf biome, Functional Groups M1.2 and M1.6.
- ¶2 SEEA EA para 4.1. "Ecosystem extent is the size of an ecosystem asset."
- ¶3 IUCN GET M1.2 Ecological Traits description.
- ¶4 IUCN GET M1.2. Kelps can reach "up to 30 m in length" and grow "up to 0.5 m/day."
- ¶5 IUCN GET M1.2 Distribution. "Nearshore rocky reefs to depths of 30 m in temperate and polar waters."
- ¶6 IUCN GET M1.2 Distribution. "Absent from warm tropical waters but present in upwelling zones off Oman, Namibia, Cape Verde, Peru and the Galapagos."

7. ¶17 IUCN GET M1.6 Ecological Traits. "Submerged rocky reefs host trophically complex communities lacking a dense macroalgal canopy."
8. ¶18 IUCN GET M1.6. "Algal productivity and abundance decline with depth due to diminution of light and are also kept in check by periodic storms and a diversity of herbivorous fish, molluscs and echinoderms."
9. ¶19 IUCN GET M1.2. "Herbivores keep epiphytes in check, but kelp sensitivity to herbivores makes the forests prone to complex trophic cascades."
0. ¶10 Remote sensing of subtidal habitats is addressed generally in TG-4.1 Remote Sensing Data.
1. ¶11 Water column correction methods are an active area of research in marine remote sensing.
2. ¶12 SEEA EA para 3.11. "Marine ecosystems are not concentrated near one surface (i.e. the air-land/water interface) but extend throughout the water column and include the underlying sediment and seabed."
3. ¶13 Giant kelp (*Macrocystis pyrifera*) forms floating surface canopies visible from satellites; other genera form sub-surface canopies.
4. ¶14 Bennett, S., Wernberg, T., De Bettignies, T., Kendrick, G.A., Anderson, R.J., Bolton, J.J., Rodgers, K.L., Shears, N.T., Leclerc, J.C., Leveque, L., Davoult, D. (2015). 'Canopy interactions and physical stress gradients in subtidal communities'. *Ecology Letters* 18(7): 677-686.
5. ¶15 UN Environment World Conservation Monitoring Centre Ocean Data Viewer provides global habitat data at moderate resolution.
6. ¶16 Multi-sensor approaches combining optical and acoustic data improve benthic habitat mapping coverage.
7. ¶17 Species distribution modelling can extend point-based survey data to estimate ecosystem extent across larger areas.
8. ¶18 SEEA EA para 4.10 and Table 4.1. The standard ecosystem extent account distinguishes additions, reductions, and conversions/reclassifications from other ecosystem types; reclassifications sum to zero at the total level across the accounting area.
9. ¶19 IUCN GET M1.2. "Trophic cascades when declines in top predators release herbivore populations from top-down regulation... may drastically reduce the abundance of kelps and dependent biota, and lead to replacement of the forests by urchin barrens, which persist as an alternative stable state."
0. ¶20 SEEA EA para 5.1. "Ecosystem condition accounts record information on the quality of ecosystem assets."
1. ¶21 SEEA EA para 5.32 and Table 5.1. Condition characteristics are grouped into six classes: physical state (A1), chemical state (A2), compositional state (B1), structural state (B2), functional state (B3), and landscape/seascape characteristics (C1).
2. ¶22 IUCN GET M1.2. "Truncated thermal niches limit the occurrence of kelps in warm waters."
3. ¶23 Marine heatwave impacts on kelp documented in Western Australia, eastern Tasmania, and other temperate regions. See Wernberg, T., Bennett, S., Babcock, R.C. et al. (2016). 'Climate-driven regime shift of a temperate marine ecosystem'. *Science* 353(6295): 169-172.
4. ¶24 Ocean acidification effects on calcifying organisms may have indirect effects on kelp community structure.
5. ¶25 IUCN GET M1.2. "Storms may dislodge kelps, creating gaps that may be maintained by herbivores or rapidly recolonized."
6. ¶26 SEEA EA para 5.35-5.48 on reference conditions.
7. ¶27 Documentation of reference condition selection is essential for transparent condition accounting.
8. ¶28 SEEA EA Chapter 6 on ecosystem services.
9. ¶29 CPC Version 2.1 includes wild sea urchins (04521) and farmed sea urchins (04522) as classified products.
0. ¶30 IUCN GET M1.2. "The structure and diversity of life in kelp canopies provide forage for seabirds and mammals, such as gulls and sea otters, while small fish find refuge from predators among the kelp fronds."
1. ¶31 SEEA EA para 6.42-6.43 on nursery population and habitat maintenance services as intermediate services.
2. ¶32 SEEA EA describes nursery and habitat services as intermediate services that support the supply of other ecosystem services (notably provisioning biomass via associated fisheries); their monetary value must be derived by attribution to the habitat, not equated with the full resource rent of the associated fishery.
3. ¶33 Carbon sequestration by kelp forests is an emerging research area with considerable uncertainty regarding magnitude and pathways.
4. ¶34 Krause-Jensen, D. and Duarte, C.M. (2016). 'Substantial role of macroalgae in marine carbon sequestration'. *Nature Geoscience* 9: 737-742. DOI: 10.1038/ngeo2790. This paper establishes the conceptual framework for macroalgal export to the deep sea (>200 m) as a long-term carbon sequestration pathway. The 0.43 t C/ha/yr export coefficient used in the worked example represents kelp-derived carbon estimated to reach depths greater than 200 m, where long-term sequestration is assumed. Plausible uncertainty range: approximately 0.1–0.9 t C/ha/yr, reflecting variation across species, biogeographic settings, and methodological choices in the macroalgal carbon export literature (Krause-Jensen & Duarte 2016 and subsequent syntheses). This coefficient is not suitable for national GHG inventory use and is provided here for illustrative accounting purposes only.
5. ¶35 SEEA EA Technical Recommendations on climate regulation – carbon sequestration. "Assessments of this service should only consider carbon stored long-term (i.e. at least several decades) in the ecosystem."
6. ¶36 Empirical wave-attenuation studies for kelp canopies include work on *Macrocystis pyrifera* in southern California (seafloor interaction reduces wave energy flux by approximately 12% with a further approximately 7% reduction over established canopies), *Laminaria hyperborea* in Norway (reductions reported up to approximately 60% through dense canopy), and *Ecklonia radiata* in shallow Australian coastal bays. Reported reductions range across approximately 7–60% depending on species, canopy density, bathymetry, and wave period.

7. ¶37 Nutrient uptake by kelp can reduce eutrophication impacts in coastal waters.
8. ¶38 Recreational diving and snorkelling in kelp forests contributes to coastal tourism economies.
9. ¶39 Long-term monitoring programmes such as PISCO provide valuable baseline data for condition assessment.
0. ¶40 Cultural services provided by kelp forests to Indigenous communities documented in multiple regions.
1. ¶41 Development of kelp-specific remote sensing algorithms is an active research area.
2. ¶42 Early warning indicators of kelp forest decline could support adaptive management.
3. ¶43 Coordination with IPCC and blue carbon initiatives needed to establish appropriate accounting treatment for kelp carbon.
4. ¶44 Primary valuation studies needed to support benefit transfer approaches for kelp forest ecosystem services.

DRAFT