Types of damage in cold-water corals

Technical framework for assessing damage, stress and cumulative effects

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Revised edition 2.4 – APA 7 format

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Updated with findings from IMR 2026-14 (VDWS Transition)
Systematic classification keys (clavis) in Chapter 10
Calibrated register and refinements following technical quality assurance
Roadmap to calibrated status (Chapter 16.2)
Rev. 2.0: revised decision keys, Nature Diversity Act model (Sections 4, 5 and 8–12, cf. Section 7), updated source basis and unified threshold model.
Rev. 2.1: generic damage grades (colony level), conditional Section 9 of the Nature Diversity Act, exhaustive Key 5, strengthened source criticism (Table 6.3) and b-MBI caveat.
Rev. 2.2: consistent conditional Section 9 of the Nature Diversity Act (Chapter 10.6 and worked example), corrected b-MBI caveat, Key 2 boundary closed at 70%, completed Nature Diversity Act references, full precautionary-principle wording in the executive summary, and species-name, roadmap and pagination corrections.
Rev. 2.3: Key 4 revised so that damage severity is explicit in the reversibility assessment and mechanical damage can reach R2, R3b and R4; Grade IV leads to R4; Key 5 requires evidence level 1 or 2 for T1; the 20–50-year interval is covered by R3b.
Rev. 2.4: Key 3 distinguishes measured from modelled supporting parameters; Key 4 step 1 renamed to mechanical or mechanically dominated damage (codes A–C); the worked example states why it remains at the basic level.

Executive summary

Document status: The framework is a structured decision- and interpretation-support tool. Classifications and measure categories are operational and indicative, and cannot on their own replace site-specific technical assessment, supplementary data collection or ordinary administrative discretion. **The framework is not calibrated against a standardised reference dataset, and the classifications should therefore be applied consistently within the same project or data series.** All use is subject to the qualifications set out in Chapters 1.2, 1.4 and 14. See Chapter 16.2 for the roadmap towards calibrated status.

This document presents a structured technical framework for classifying and assessing damage in cold-water corals, with particular relevance to reef-forming species such as *Desmophyllum pertusum* (formerly *Lophelia pertusa*). The framework combines established scientific literature with operational field methodology and legal applicability.

The purpose is not to establish cause without documentation, but to:

- Systematise observations
- Differentiate between damage mechanisms
- Make cumulative effects visible
- Clarify uncertainty and evidence level

The document operates with three evidence levels (directly documented damage, consistent mechanism and hypothetical association), which reduces the risk of over-interpretation and strengthens verifiability in management processes.

In revised edition 1.2, the framework was updated with findings from the Institute of Marine Research's VDWS Transition project (Dunlop et al., 2026). The updates comprise quantitative sedimentation thresholds, species-specific sensitivity classifications, new field methods (visual health index and b-MBI), and empirical support for the finding that sub-lethal stress may be present without visible damage.

In revised edition 1.3, a new Chapter 10 has been added with five systematic classification keys (clavis) that make it possible to classify damage step by step: primary damage mechanism, damage severity, evidence level, reversibility and measure assessment. The keys operationalise the theoretical content of the framework into verifiable field tools.

In revised edition 1.4, the register has been calibrated following technical feedback and quality assurance. Thresholds are described as indicative levels, classifications are formulated as indicative assessments rather than categorical conclusions, and the measure categories are explicitly defined as decision support for further administrative consideration.

In revised edition 1.5, an explicit acknowledgement has been added that the framework is not calibrated against a standardised reference dataset, together with a roadmap (Chapter 16.2) specifying what is required to achieve calibrated status. This provides a transparent development trajectory and a concrete basis for collaboration.

Relationship to Sections 4, 5 and 8–12 of the Nature Diversity Act

The framework is designed to form part of the competent authority's assessment of the management objectives in Sections 4 and 5 of the Nature Diversity Act and the principles in Sections 8–12, cf. Section 7. The core technical basis lies in Sections 4, 5 and 8–10, while Sections 11 and 12 are case-specific supplementary principles applied only where they are actually relevant to a specific measure.

The framework is a technical decision- and interpretation-support tool. It provides a structured basis for the competent authority's assessment of the management objectives in Sections 4 and 5 and the principles in Sections 8–12 of the Nature Diversity Act, cf. Section 7 of the Nature Diversity Act. The framework does not make the final legal assessment, establish causation without supporting evidence or determine cost liability under Section 11 of the Nature Diversity Act. The final assessment and reasons rest with the competent management authority.

Section 4 of the Nature Diversity Act – Management objectives for habitat types and ecosystems: The framework links damage types and severity to the condition of the habitat types and ecosystems to be managed.

Section 5 of the Nature Diversity Act – Management objectives for species: The classification of mechanism, severity and reversibility supports the assessment of the population status and trend of the species.

Section 8 of the Nature Diversity Act – The knowledge base: Structured damage analysis strengthens the knowledge base by systematising observations and linking them to established literature.

Section 9 of the Nature Diversity Act – The precautionary principle: Relevant where the knowledge base regarding the effects on the natural environment is insufficient. The aim shall then be to avoid possible significant damage. Where there is a risk of serious or irreversible damage, a lack of knowledge cannot justify postponing or omitting management measures.

Section 10 of the Nature Diversity Act – The ecosystem approach and cumulative environmental effects: The document places particular emphasis on cumulative effects and multiple-stressor interactions.

Section 11 of the Nature Diversity Act – The operator bears the costs of environmental degradation: Relevant only where an identifiable operator and cost liability can be assessed under relevant legislation. The framework does not determine cost liability.

Section 12 of the Nature Diversity Act – Environmentally sound techniques and methods of operation: Relevant where a specific measure concerns the choice of technique, method of operation or siting; identified damage mechanisms provide a basis for assessing alternatives.

Operational value

The document provides:

- A consolidated threshold overview for operational classification
- Diagnostic differentiation between mechanical, sediment-related and physiological impact
- A structure for the use of supporting parameters (oxygen, TOC, current, temperature)
- Methodological guidance for field and time-series analysis
- Quantitative sedimentation thresholds based on IMR report 2026-14
- Species-specific sensitivity classifications for management-relevant benthic species
- Five systematic classification keys (clavis) for step-by-step assessment

Limitations

The framework is not a statistically validated protocol. Establishing cause requires supplementary data, including hydrodynamic analyses, chemical measurements and time series.

Development status

The framework is in a development phase. It is based on a focused selection of key works, not on a systematic literature review, and is not calibrated against a standardised reference dataset. Chapter 16.2 specifies a roadmap with concrete milestones for achieving formally calibrated status, structured in three dimensions:

- **Underlying data (D1–D4):** reference dataset from several sites and seasons, with linked environmental parameters.
- **Methodological validation (M1–M5):** inter-calibration between observers, threshold validation, independent field validation.
- **Institutional anchoring (I1–I4):** peer review, consultation with IMR/NINA/the Norwegian Environment Agency, integration with existing protocols.

Through this roadmap, the framework's current limitations and development trajectory are made visible in a transparent manner.

Overall assessment

The framework represents a technically strengthened and methodologically refined version of earlier work. It is scientifically grounded, verifiable, operationally applicable and legally relevant, while remaining transparent about its own development needs.

1. Introduction

Cold-water corals constitute structurally complex, slow-growing marine habitats of high ecological value. They function as three-dimensional ecosystem engineers and provide

habitat for a wide range of benthic and pelagic species (Roberts et al., 2006; Freiwald et al., 2004).

In Norwegian waters, reef-forming cold-water corals occur particularly in fjord systems and on the continental shelf, where they may be exposed to human activity such as fisheries, aquaculture, infrastructure and changes in hydrodynamic conditions (Fosså et al., 2002; ICES, 2004).

Damage to cold-water corals can be of very different character. Some impacts produce acute and visible structural damage, while others develop gradually through physiological stress, reduced vitality and secondary biological processes (Henry & Roberts, 2017).

The primary reef-forming species is referred to in this document as *Desmophyllum pertusum* (Linnaeus, 1758), previously known as *Lophelia pertusa*.

1.1 Purpose

The purpose of this document is to establish a comprehensive and systematic technical framework for:

- Classifying types of damage in cold-water corals
- Distinguishing between primary impact and secondary damage processes
- Structured assessment of cumulative effects
- Consistent use in the field, in analysis and in management processes

1.2 Scope and methodological clarification

This document does not establish specific impact sources without supporting data. It describes biologically consistent mechanisms based on established literature. An explicit distinction is drawn between observation, technical assessment and causal interpretation.

Any determination of cause requires hydrodynamic analyses, chemical measurements, time series and spatial covariation analysis.

1.3 Transferability between species

The framework is primarily developed on the basis of reef-forming stony corals such as *D. pertusum*, but builds on processes that are largely shared with other sessile colony-forming organisms.

The VDWS Transition project (Dunlop et al., 2026) has documented that sensitivity to organic impact varies substantially between species. See Chapter 6.4 for a full overview.

1.4 Document status

This document represents a structured technical framework. It is not a validated scientific protocol with inter-calibration and statistically tested thresholds. The percentage levels given are used as operational classification intervals.

1.5 Reference and source basis

The document is structured in accordance with the APA 7 standard. Central mechanisms are grounded in established primary literature (Fosså et al., 2002; Roberts et al., 2006; Henry & Roberts, 2017; Davies et al., 2009; Kutti et al., 2022; Weinnig et al., 2020; Dunlop et al., 2021; Dunlop et al., 2026).

The framework is built on a focused selection of key works on cold-water corals, Norwegian waters and aquaculture-related impact, and not on a systematic literature review. This gives the document a clear and delimited technical basis, but at the same time means that a broader literature basis should be sought in further development and formal validation (cf. Chapters 14 and 16.2).

2. Mechanical damage

Direct physical impact is one of the best-documented causes of damage to cold-water corals (Fosså et al., 2002; Roberts et al., 2006).

2.1 Direct physical destruction

Bottom contact from fishing gear, anchoring and other physical impact can lead to torn-off branch structures, exposed calcareous skeleton, fragmentation of colonies and collapsed reef structures.

Diagnostic features

- Sharp, pale fracture surfaces
- Local, discrete distribution of damage
- Intact polyps in direct association with the fracture

A vertical mortality gradient with greater tissue loss near the base may be consistent with sediment-related impact, but is not diagnostic on its own; the absence of such a gradient may indicate mechanical damage.

2.2 Sub-lethal mechanical impact

Repeated contact, vibration or light dragging can produce reduced polyp activity, temporary retraction and altered growth form. Experimental studies show that a simultaneous temperature increase can reduce the capacity for recovery after short-term stress exposure (Weinnig et al., 2020).

3. Sediment-related damage

Fine-particulate sediment represents a well-known stress factor for cold-water corals, particularly in areas with reduced current velocity or increased particle input (Larsson & Purser, 2011; Larsson et al., 2013; Henry & Roberts, 2017).

3.1 Physiological mechanism

Cold-water corals depend on effective particle filtration. Sediment can cover the polyps, increase the energy spent on cleaning and mucus production, and reduce the net energy balance. Prolonged sediment impact can lead to gradual polyp death, reduced colony vitality and local tissue necrosis.

Indicative sedimentation levels for health effects

The VDWS Transition project (Dunlop et al., 2026) has documented indicative sedimentation levels at which health effects have been observed in management-relevant benthic species in Norwegian waters. The levels are based on modelled accumulated organic sedimentation (accumulated over approx. two years, cf. IMR 2026-14) and represent operational reference values that must be interpreted site-specifically, not universal biological thresholds:

- **Fan sponge:** Visible tissue degradation and reduced LMS have been observed in association with high sedimentation. The absence of individuals within 250 m of certain farms may be consistent with strong impact, but alternative explanations (habitat preferences, natural variation) cannot readily be ruled out.
- ***Geodia* sponge:** A substantial cellular stress response has been observed in association with levels > 1000 g/m² (accumulated over two years) and within 300 m in the main current direction.
- ***Primnoa resedaeformis*:** Visible tissue degradation has been observed in association with levels > 2000 g/m² (accumulated over two years), within 10–500 m.
- ***Paragorgia arborea* ('bubblegum coral'):** Metabolic and molecular responses have been observed in association with levels > 1000 g/m² (accumulated over two years) and within 200 m.

3.2 Diagnostic features

- Increased mortality near the colony base
- Vertical mortality gradient
- Presence of fine-particulate material between branch structures

3.3 Chronic vs. episodic impact

Episodic sediment input can be reversible. Chronic input can produce gradual loss of function, increased susceptibility to secondary colonisation and reduced structural stability.

The diel rhythm of polyp activity in *Primnoa resedaeformis* and *Paragorgia arborea* is disturbed by chronic sedimentation of 0.5 g/m²/day, corresponding to levels modelled within approx. 300 m in the main current direction at the farms studied (Dunlop et al., 2026).

4. Organic loading and oxygen stress

Organic enrichment can affect cold-water corals indirectly through increased microbial oxygen consumption and altered biogeochemistry (Dunlop et al., 2021; Kutti et al., 2022).

4.1 Metabolic depression

Studies of *D. pertusum* show that increased organic loading can lead to metabolic depression, reduced energy reserves and a lowered growth rate (Kutti et al., 2022).

Indicative exposure levels from laboratory experiments

Laboratory experiments from VDWS provide concrete exposure levels at which physiological stress responses have been observed (Dunlop et al., 2026). The values apply to the species tested under experimental conditions and cannot be transferred directly to all field situations:

- ***Primnoa resedaeformis*:** Reduced polyp activity, tissue breakdown and increased mortality have been observed in association with exposure levels of 5–10 g/m²/day. The diel rhythm is disturbed already at exposure levels of 0.5 g/m²/day.
- ***Paragorgia arborea*:** Responses similar to those of *Primnoa*.
- ***D. pertusum*:** Least sensitive to organic material.

Note: Values given as g/m²/day are exposure rates from laboratory experiments and cannot be compared directly with accumulated field values given in g/m².

4.2 Oxygen stress

Increased organic input can lead to reduced oxygen concentration in bottom water, which can reduce polyp activity, increase the risk of tissue loss and reinforce cumulative effects (Roberts & Cairns, 2014).

4.3 Multiple-stressor interactions

A combination of temperature increase and other stress exposure can produce a stronger negative effect than either factor in isolation (Weinnig et al., 2020).

Pharmaceuticals as an additional stressor

VDWS documents delousing agents as an additional stressor (Dunlop et al., 2026):

- **Hydrogen peroxide:** LC50 = 27.20 mg/L for stony-coral larvae.
- **Azamethiphos:** EC50 = 1.89 µg/L, sub-lethal effects up to 200 m.
- **Emamectin benzoate:** Metabolic and behavioural changes in adult stony corals.

5. Secondary colonisation and biological overgrowth

The exposed calcareous skeleton provides a substrate for hydroids, bryozoans, sponges and other epibionts (Henry & Roberts, 2017).

5.1 Primary vs. secondary process

Secondary colonisation is not necessarily a primary cause of damage, but can be a consequence of earlier tissue loss and a self-reinforcing driver of progression.

Molecular methods can reveal sub-lethal responses not captured by visual criteria (Dunlop et al., 2026). It is not sufficiently documented that such changes generally occur before visible secondary colonisation.

5.2 Indicative classification of overgrowth

- < 30% overgrowth → Grade I (limited impact)
- 30–<70% → Grade II (moderate impact)
- 70–<85% → Grade III (extensive impact)
- ≥85% → Grade IV (very extensive impact)

Note: The threshold values indicate the proportion of the analysis unit affected. A distinction must be made between the percentage damage to a single colony and the percentage of habitat, area or occurrence affected; these are different analysis units that do not necessarily have the same threshold values.

6. Cumulative effects and progression dynamics

6.1 Possible development trajectories

- Acute mechanical damage → local regeneration
- Mechanical damage + sediment → progression
- Organic loading → physiological weakening
- Multiple stressors → accelerated collapse

6.2 Reversibility

Early stages can be reversible. Later stages with extensive structural loss are in practice considered irreversible on a management timescale (Roberts et al., 2006).

6.3 Extended overview of stress and impact factors (indicative)

No.	Stress factor	Cause	Symptoms	Long-term effect	Implication	Ref.
6.3.1	Temperature	Sustained increase	Reduced polyp activity	Reduced recovery capacity	Reinforces others	Weinnig et al. (2020)
6.3.2	Oxygen	Hypoxia	Polyp inactivity	Increased mortality	Selective death	Roberts & Cairns (2014)
6.3.3	Organic loading	Particulate material	Reduced filtration	Habitat degradation	Gradual weakening	Kutti et al. (2022)
6.3.4	pH reduction	Carbonate system	Reduced calcification	Thinner skeleton	Reduced resistance	Roberts & Cairns (2014)

No.	Stress factor	Cause	Symptoms	Long-term effect	Implication	Ref.
6.3.5	Contaminants	Heavy metals	Sub-lethal effects	Impaired reproduction	Difficult to detect	ICES (2004)
6.3.6	Sediment	Fine-particulate	Polyp smothering	Colony loss	Vertical gradient	Larsson et al. (2013)
6.3.7	Substrate	Slides, vibration	Destabilised colonies	Permanent loss	Increased vulnerability	Fosså et al. (2002)
6.3.8	Species change	Change in food supply	Overgrowth	Loss of function	Altered balance	Henry & Roberts (2017)
6.3.9	Disease	Microbial imbalance	Irregular tissue loss	Increased mortality	Necrosis	Roberts et al. (2006)
6.3.10	Reduced recruitment	Loss of reef structure	Older colonies	Loss of continuity	Structural	Fosså et al. (2002)
6.3.11	**Pharmaceuticals**	Delousing agents	Larval mortality	Population decline	Reproductive pot.	Dunlop et al. (2026)

Note: Table 6.3 is an indicative overview. Several of the causal chains rest on broad overview sources and are not directly documented for each individual claim; they are read as operational working hypotheses pending targeted primary sources. Weinnig et al. (2020) concerns the effect of temperature on recovery after short-term exposure and does not support a general claim about all stressors.

6.4 Species-specific sensitivity classification

Based on Dunlop et al. (2026). The classification concerns sensitivity to the exposures studied (organic loading and sedimentation), not general species sensitivity; visual indices are species-dependent.

Species	Sensitivity	Certainty	Comment
Fan sponge (*Phakellia* spp.)	Very high	High	Most sensitive taxon in the experiment; alternative explanations (historical impact, substrate, survey coverage) should be assessed
Geodia sponge (*Geodia barretti*)	High	High	Some individuals tolerant
Paragorgia arborea (bubblegum coral)	Moderate–high	High	Visually difficult to detect
Primnoa resedaeformis	Moderate–high	Moderate	Conflicting signals
Acesta excavata	Low	Moderate	More robust
Paramuricea placomus	Unknown	Low	Sample too small
Desmophyllum pertusum	Unknown (field)	Low (field)	Least sensitive of the four coral taxa studied in the laboratory experiment; larvae highly sensitive

7. Operational synthesis of damage mechanisms

7.1 Primary damage processes

- Direct physical destruction (Fosså et al., 2002; Roberts et al., 2006)
- Sediment-induced energy stress (Larsson et al., 2013; Baussant et al., 2022)
- Organic loading and metabolic depression (Kutti et al., 2022)
- Temperature-related reduction in the capacity for recovery (Weinnig et al., 2020)
- Pharmaceutical exposure from aquaculture (Dunlop et al., 2026)

7.2 Secondary and self-reinforcing processes

- Secondary colonisation
- Increased sediment accumulation
- Reduced recruitment
- Structural destabilisation

7.3 Diagnostic differentiation

Pattern	Most consistent mechanism
Sharp, discrete fracture surfaces	Mechanical impact
Vertical mortality gradient	Sediment stress
Uniform reduction in vitality without fractures	Physiological stress
Overgrowth of dead skeleton	Secondary process
Disturbed polyp activity without visible damage	Sub-lethal organic impact

8. Evidence level and strength of interpretation

The framework operates with three evidence levels:

Level 1 – Directly documented damage

- Directly observed or documented exposure or damage event with corresponding damage
- Robust before/after data with documented impact

Level 2 – Consistent mechanism

- Damage pattern consistent with established literature
- Absence of more plausible alternative explanations

- Temporal and spatial correspondence with a known event, with pattern recognition and systematic assessment of alternative explanations

LMS can strengthen assessments at this level (Dunlop et al., 2026).

Level 3 – Hypothetical association

- Biologically plausible
- Insufficient underlying data
- Requires further analysis

9. Overall operational classification

Classification	Indicative proportion of functional loss	Operational interpretation
Limited impact	< 30%	Local damage
Moderate impact	30–<70%	Substantial weakening
Extensive impact	70–<85%	Critical condition
Very extensive impact	≥85%	Indicative functional breakdown

10. Systematic classification keys (clavis)

This chapter presents five systematic keys following the principles of the traditional dichotomous clavis, familiar from taxonomic fieldwork. The keys operationalise Chapters 2–9 of the framework into a step-by-step tool for classification in the field and in analysis.

Important clarification: The keys are a structured decision- and interpretation-support tool, not a validated diagnostic protocol. The results are indicative assessments that indicate the most consistent mechanisms, grades and measure categories – they do not replace site-specific technical assessment, supplementary data collection or ordinary administrative discretion. A code such as E-II-2-R3a-T2 expresses a structured working hypothesis, not a validated classification.

10.1 About the keys

A clavis is a hierarchical decision tree. At each step, one of two (or more) mutually exclusive alternatives is chosen. The choice leads either to the next step or to a classification result. Such a structure reduces subjectivity and makes assessments verifiable.

The five keys are:

- **Key 1:** Primary damage mechanism (which type of damage?)
- **Key 2:** Damage severity (how serious?)
- **Key 3:** Evidence level (how certain is the assessment?)
- **Key 4:** Reversibility and progression potential (what happens next?)

- **Key 5:** Measure assessment (what should be done?)

Instructions for use: Always start with Key 1. Work your way down – answer each step based on the observation. When you reach a result, move on to the next key. All five keys together give an overall classification covering type of damage, severity, certainty, prognosis and measures.

Prerequisite: The keys presuppose systematic field documentation in accordance with Chapter 11.1. Where an observational basis is lacking, this shall be stated as part of the uncertainty assessment.

10.2 Key 1: Primary damage mechanism

Purpose: To identify which principal mechanism best explains the observed damage. Results refer to the relevant chapters of the framework.

Start here.

1a	The damage comprises visible, sharply delimited fracture surfaces or torn-off structures	→ **Step 2**
1b	The damage lacks acute fractures and develops gradually	→ **Step 4**

2a	The fracture surfaces are sharp and pale (recent), without a vertical mortality gradient, with intact polyps in association with the fracture	→ **A – Acute mechanical damage (Chapter 2.1)**
2b	Fracture surfaces occur together with extensive secondary colonisation or a vertical gradient	→ **Step 3**

3a	Secondary colonisation is dominant, fracture surfaces are older (dark/overgrown)	→ **B – Historical mechanical damage + secondary process (Chapters 2 + 5)**
3b	A vertical mortality gradient dominates together with fractures	→ **C – Combined mechanical + sediment loading (Chapters 2 + 3)**

4a	Visible fine-particulate sediment on/between branch structures, and/or a vertical mortality gradient (more dead tissue at the base)	→ **Step 5**
4b	No visible sediment cover or vertical gradient	→ **Step 7**

5a	The sediment is fine-particulate and appears organically enriched (malodorous, biofilm, dark colour), OR a source of organic discharge is known nearby	→ **Step 6**
5b	The sediment is mineral/coarse or without signs of organic enrichment	→ **D – Pure sediment loading (Chapter 3)**

6a	Modelled or measured accumulated sedimentation elevated (e.g. > 1000 g/m² over two years, cf. IMR 2026-14), assessed together with current direction, exposure period and species-specific responses. Distance to source is not used alone as a classification criterion.	→ **E – Sediment-induced damage with organic enrichment (Chapters 3 + 4)**
6b	Quantification is lacking, but the pattern is consistent with organic impact	→ **E – Sediment-induced damage with organic enrichment (Chapters 3 + 4), evidence level 2–3**

7a	Reduced polyp activity OR increased mucus production, AND a known or probable organic source nearby	→ **F – Possible organic loading / metabolic depression (working hypothesis, Chapter 4)**
7b	Overgrowth by epibionts (hydrozoans, bryozoans, sponges) on dead skeleton dominates	→ **G – Secondary colonisation (Chapter 5)**
7c	Reduced polyp activity or other signs of stress without a known source, no overgrowth, no supporting data	→ **H – Unspecified physiological stress (requires further analysis)**

Overview – results from Key 1

Code	Classification	Main chapter	Typical diagnostics
A	Acute mechanical damage	Chapter 2.1	Sharp, pale fracture surfaces
B	Historical mechanical + secondary	Chapters 2 + 5	Older fractures + overgrowth
C	Mechanical + sediment	Chapters 2 + 3	Fractures + vertical gradient
D	Pure sediment loading	Chapter 3	Mineral sediment, gradient
E	Sediment + organic enrichment	Chapters 3 + 4	Organic sediment, known source
F	Possible organic loading (working hypothesis)	Chapter 4	Reduced polyp activity – requires supporting data
G	Secondary colonisation	Chapter 5	Overgrowth by epibionts
H	Unspecified physiological stress	Chapter 4	Requires further analysis

10.3 Key 2: Damage severity

Purpose: To determine the severity based on the percentage of the colony or habitat affected. Used together with the result from Key 1.

Basis: An estimate of the proportion of the colony/habitat affected (tissue loss, overgrowth, reduced vitality or sediment cover). Use the point-intercept method on photographs, quadrat methods or a visual % assessment.

1a	Less than 30% of the colony/area shows signs of impact	→ **Grade I – limited impact**
1b	30% or more of the colony/area is affected	→ **Step 2**

2a	30% to <70% of the colony/area is affected	→ **Grade II – moderate impact**
2b	70% or more of the colony/area is affected	→ **Step 3**

3a	Between 70% and below 85% affected, but with functional structure still observable	→ **Grade III – extensive impact**
3b	85% or more affected, functional structure in practice lost	→ **Grade IV – very extensive impact**

Overview – damage severity

Grade	Proportion affected	Operational interpretation	Management relevance
I – limited	< 30%	Local damage, limited significance	Monitoring recommended
II – moderate	30–<70%	Substantial weakening, function partly intact	Measures should be considered
III – extensive	70–<85%	Critical condition, elevated risk of progression	The need for active measures should be assessed
IV – very extensive	≥85%	Indicative functional breakdown	Practically irreversible – prevention

Note: The boundaries are operational assessment levels, not universal biological thresholds. In case of doubt between two grades, state the lower one and describe the uncertainty. The percentage boundaries apply to the proportion of a single colony affected (the analysis unit); habitat- or area-level assessment requires a separate defined analysis unit, and Grade IV at habitat level is described as 'indicative functional loss within a defined analysis unit'.

10.4 Key 3: Evidence level

Purpose: To assess how certain the classification from Keys 1 and 2 is. This level should be stated in reports and technical decision bases.

1a	Directly observed or documented exposure/damage event with corresponding damage, or robust before/after data with documented impact	→ **Level 1 – Directly documented damage**
1b	No direct documentation; the assessment is based on the damage pattern	→ **Step 2**

2a	The damage pattern is consistent with established literature, or shows temporal/spatial correspondence with a known event, AND there are no more plausible alternative explanations	→ **Step 3**
2b	The damage pattern is biologically plausible, but alternative explanations cannot be ruled out	→ **Level 3 – Hypothetical association**

3a	Measured supporting parameters are available (O_2, TOC, sediment, LMS or equivalent; b-MBI is regarded as a supplementary indicator under development and does not on its own raise the evidence level) and are consistent with the interpretation	→ **Level 2 – Consistent mechanism (strengthened)**
3b	Visual observations and/or modelled values only, without measured quantitative supporting data	→ **Level 2 – Consistent mechanism (basic)**

Overview – evidence level

Level	Criteria	Strength of interpretation	Use in technical decision basis
1 – Direct	Directly observed/documented exposure or damage event with corresponding damage; or robust before/after data	High	Can be included in the technical decision basis
2 – Consistent	Pattern matches the literature, no better alternative	Moderate	Strengthened by supporting parameters
3 – Hypothetical	Biologically plausible, but uncertain	Low	Requires further analysis

10.5 Key 4: Reversibility and progression potential

Purpose: To assess whether the damage is reversible, whether progression is likely, and thus how urgent measures are. For gradual stress processes (codes D–H from Key 1), the progression model in Chapter 12.1 is used as the basis. For acute mechanical damage (codes A–C), a separate logic applies, reflecting the fact that such damage does not form part of the progression model.

1a	The damage is classified as mechanical or mechanically dominated damage (codes A–C from Key 1)	→ **Step 4**
1b	The damage is classified as sediment- or organic-related stress (codes D–H from Key 1)	→ **Step 2**

2a	Colony at an early stage of the progression model (steps 1–3: physiological stress or reduced polyp activity without structural damage)	→ **Step 3**
2b	Colony at an intermediate stage (steps 4–5: sediment accumulation and incipient secondary colonisation)	→ **Step 5**
2c	Colony at an advanced stage (steps 6–7: advanced smothering or indicative habitat collapse)	→ **R4 – Practically irreversible on a management timescale**

3a	The stress factor is identified and can be removed or reduced (technically and administratively feasible), no further stressors expected	→ **R1 – Reversible (high capacity for recovery expected)**
3b	The stress factor persists or is difficult to remove	→ **R2 – Conditionally reversible (risk of progression if the stress persists)**

4a	Mechanical damage comprises < 30% of the analysis unit (Grade I), and recurrence of the damage sequence can be avoided	→ **R1 – Reversible (local regeneration expected)**
4b	Mechanical damage comprises < 30% of the analysis unit (Grade I), but persistent or repeated gear load is documented	→ **R2 – Conditionally reversible (risk of progression if the loading persists)**
4c	Mechanical damage comprises 30–<70% of the analysis unit (Grade II), without documented persistent loading	→ **R3a – Partially reversible (regeneration over years to decades)**
4d	Mechanical damage comprises 30–<70% (Grade II) with documented persistent or repeated loading, or 70–<85% (Grade III)	→ **R3b – Accelerated collapse likely**
4e	Mechanical damage comprises ≥ 85% (Grade IV), functional structure is in practice lost, or reef structure is fragmented into coral rubble	→ **R4 – Practically irreversible on a management timescale**

5a	A single principal stressor identified, no documented concurrent stressors, the loading assessed as stable or declining	→ **R3a – Partially reversible (regeneration over years to decades)**
5b	Multiple stressors act concurrently, or the loading is assessed as increasing	→ **R3b – Accelerated collapse likely**

Overview – reversibility

Code	Description	Time horizon	Measure indication
R1	Reversible	Months to 1–2 years	Removal of stress sufficient
R2	Conditionally reversible	1–5 years with measures	Active measure required
R3a	Partially reversible	5–20 years	Long-term monitoring
R3b	Accelerated collapse	20–50 years, or accelerating development towards R4	Immediate measures
R4	Practically irreversible	> 50 years / not within a management timescale	Focus on prevention elsewhere

10.6 Key 5: Measure assessment under the Nature Diversity Act

Purpose: To combine the results from Keys 1–4 into an operational measure recommendation, linked to Sections 4, 5 and 8–12 of the Nature Diversity Act, cf. Section 7.

> The measure categories (T1–T5) are decision support for further administrative consideration, not normative outcomes. The management objectives in Sections 4 and 5 of the Nature Diversity Act and the principles in Sections 8–12, cf. Section 7, must be assessed specifically in the individual case. The key provides a structured entry point to such assessments but does not replace them.
>
> The measure categories are technical decision support. They do not automatically trigger specific statutory provisions. The relevance of Sections 8–12 of the Nature Diversity Act must be assessed specifically by the competent management authority under Section 7. Sections 4 and 5 set the relevant management objectives. Section 9 is assessed specifically where the knowledge base is insufficient and the damage potential makes the provision relevant. Section 10 is assessed where cumulative loading is relevant to the decision.

Basis: Use the output from the four preceding keys: damage mechanism (A–H), grade (I–IV), evidence level (1–3) and reversibility (R1–R4).

1a	The damage is classified as documented acute mechanical damage (code A) with evidence level 1, irrespective of grade	**→ Step 2 (first assess whether the conditions for T1 are met; otherwise the case is handled further in step 3)**
1b	Other mechanism codes (B–H) or evidence level 2–3	**→ Step 2**

2a	Damage grade III or IV (≥70%) AND reversibility R3b or R4 (accelerated/practically irreversible) AND evidence level 1 or 2	**→ T1 – immediate measures should be considered. Sections 4 and 5 of the Nature Diversity Act set the management objectives; Section 9 is assessed specifically where the knowledge base is insufficient and the damage potential makes the provision relevant; Section 12 where the measure concerns technique, method of operation or siting.**
2b	Damage grade lower than III, reversibility R1–R3a, or evidence level 3	**→ Step 3**

3a	Damage grade II–IV with evidence level 1 or 2, and not already classified as T1	**→ T2 – the need for active measures should be assessed. Sections 4 and 5 of the Nature Diversity Act set the management objectives; Section 10 is assessed where cumulative loading is relevant; Section 12 for mitigating technique, method of operation or siting.**
3b	Grade I, or evidence level 3	**→ Step 4**

4a	Documented or likely cumulative loading from prior, ongoing and expected impacts; several simultaneous stressors are one possible case.	**→ T3 – an assessment of cumulative environmental effects is recommended (Section 10 of the Nature Diversity Act, assessed against the objectives in Sections 4 and 5); the need for targeted measures is assessed.**
4b	A single stressor or uncertainty about cumulative effects	**→ Step 5**

5a	Evidence level 3 or significant knowledge gaps requiring active data acquisition	**→ T4 – Monitoring and knowledge acquisition are recommended (Section 8 of the Nature Diversity Act; Section 9 where monitoring is combined with temporary precautionary measures)**
5b	Grade I and R1 with sufficient evidence and low damage potential, where the conditions for Section 9 of the Nature Diversity Act do not apply	**→ T5 – Passive monitoring; measures not indicated at the present time**
Otherwise	Other combinations not captured above (e.g. Grade I with R2–R3a and evidence level 1–2 without high cumulative loading)	**→ T4 – monitoring is recommended; the need for measures is assessed specifically when a new basis becomes available.**

Overview – measure categories

Code	Measure category	Primary anchoring	Conditional addition
T1	Immediate measures should be considered	Sections 4 and 5 of the Nature Diversity Act	Section 9 of the Nature Diversity Act where the knowledge base is insufficient and the damage potential makes the provision relevant; Section 10 where several simultaneous impacts occur; Section 12 for technique, method of operation or siting

Code	Measure category	Primary anchoring	Conditional addition
T2	Active measures should be considered	Sections 4 and 5 of the Nature Diversity Act	Section 9 of the Nature Diversity Act where the conditions apply; Section 10 in cases of cumulative loading; Section 12 for mitigating technique, method of operation or siting; Section 11 only where the operator and cost liability are legally relevant
T3	An assessment of cumulative environmental effects is recommended	Section 10 of the Nature Diversity Act, assessed against Sections 4 and 5	Section 9 of the Nature Diversity Act in cases of uncertainty and damage potential (precaution)
T4	Monitoring and knowledge acquisition are recommended	Section 8 of the Nature Diversity Act	Section 9 of the Nature Diversity Act where monitoring must be combined with temporary precautionary measures
T5	Passive monitoring	Section 8 of the Nature Diversity Act	Applied only where the conditions for Section 9 of the Nature Diversity Act do not apply

10.7 Overall classification – example of use

The example below shows how the five keys are used together to classify an observation.

Field observation (fictitious example)

A colony of D. pertusum is observed at approx. 180 m depth, 350 m from a fish farm. The colony shows uniformly reduced polyp activity and light sediment cover between the branch structures, with a slight vertical mortality gradient. Modelled accumulated sedimentation is estimated at 1200 g/m². Approx. 45% of the colony is affected. Current conditions indicate that the area lies downstream of the farm. LMS data are not available.

Step-by-step classification

Key	Choice	Result
Key 1 – Mechanism	1b → 4a → 5a → 6a	**E – Sediment-induced damage with organic enrichment** (Chapters 3 + 4). Rationale: vertical gradient, downstream of the farm, modelled sedimentation > 1000 g/m².
Key 2 – Grade	1b → 2a	**Grade II – moderate impact (45% affected).**
Key 3 – Evidence	1b → 2a → 3b	**Level 2 – Consistent mechanism (basic). The sedimentation figure is modelled, not measured on site; the absence of measured supporting parameters keeps the assessment at the basic level.**
Key 4 – Reversibility	1b → 2b → 5a	**R3a – Partially reversible** (intermediate stage of the progression model, single stressor). Persistent impact or additional stressors could lead to R3b.
Key 5 – Measure	1b → 2b → 3a	**T2 – Active measures should be considered** (Sections 4 and 5 of the Nature Diversity Act, together with Section 10; Section 12 for mitigating technique and alternative siting): mitigating techniques, hydrodynamic modelling, assessment of an alternative site.

Overall classification code

E-II-2-R3a-T2 – Indicative assessment: sediment-induced damage with organic enrichment, moderate grade, consistent mechanism (basic), partially reversible, active measures should be considered.

Important reservation: The classification expresses the most consistent interpretation given the available data. Alternative explanations – such as natural variation in polyp activity, local hydrodynamic turbulence, other concurrent stressors or earlier events that are not documented – cannot be fully ruled out without supplementary data. Real field cases will often have a wider scope for interpretation than this illustrative example suggests.

Recommended technical wording for the decision basis:

‘The observation is assessed as most consistent with sediment-induced damage with organic enrichment (E), damage grade II (30–<70% affected), evidence level 2 (basic), reversibility category R3a. Alternative explanations cannot be fully ruled out without supplementary data. Pursuant to Sections 4, 5 and 10 of the Nature Diversity Act, it is considered relevant to assess active measures (T2), including mitigating techniques and hydrodynamic modelling of sediment dispersal. As the knowledge base at evidence level 2 remains subject to uncertainty and the potential for damage is substantial, Section 9 of the Nature Diversity Act is also considered relevant. As the measures concern the choice of mitigating technique and possible alternative siting, Section 12 should be assessed specifically. Section 11 is relevant only where the operator and cost liability can be identified under relevant legislation. The acquisition of LMS data or other validated supporting parameters is recommended in order to strengthen the evidence level (Dunlop et al., 2026). b-MBI may be included as a supplementary indicator under development, but does not on its own raise the evidence level. The assessment is decision support and does not replace ordinary administrative discretion.’

11. Operational use in the field and in analysis

11.1 Field-based documentation

Systematic documentation is a prerequisite for using the keys in Chapter 10.

- High-resolution photographs and/or video
- A scale object in the image
- Overview image + detail image
- Documentation of the surrounding substrate
- Recording of depth, current conditions and visibility

Recommended visual health criteria in accordance with Dunlop et al. (2026): proportion of tissue loss, visible tissue degradation/discolouration, mucus production, sediment cover.

11.2 Spatial pattern recognition

- Is the damage localised or gradient-based?
- Is mortality greatest at the base or the top?
- Is the damage symmetrical or directional?
- Does the damage covary with current direction?

11.3 Use of supporting parameters

- Oxygen concentration (O_2)
- Total organic carbon (TOC)
- Sediment grain size
- Current velocity and variation

- Temperature deviation from the historical norm

Advanced supporting methods

From Dunlop et al. (2026):

- **Visual health index:** A non-invasive index for several coral and sponge species.
- **b-MBI:** A microbial indicator of organic enrichment. A supplementary indicator under development; not regionally validated for Norwegian conditions, and cannot on its own raise the evidence level or verify an impact gradient (IMR 2026-14).
- **LMS:** Cellular stress even where the visual condition is normal.

11.4 Temporal dimension and progression assessment

- Is the damage recent or established?
- Are there signs of regeneration?
- Is overgrowth at an early or advanced phase?
- Is historical documentation available?

11.5 Classification and uncertainty

When classifying according to the keys in Chapter 10, the following shall always be stated:

- Damage mechanism code (A–H)
- Damage grade (I–IV)
- Evidence level (1–3)
- Reversibility category (R1–R4)
- Measure category (T1–T5)
- Underlying data and uncertainty assessment

11.6 Application in a management context

When used in the technical decision basis, the documentation should:

- Draw a clear distinction between observation and interpretation
- State the level of uncertainty
- Describe alternative explanations
- Assess cumulative effects (Section 10 of the Nature Diversity Act)

11.7 Operational assessment principles

A. Observation is kept separate from interpretation. Descriptive documentation first, technical assessment kept separate (cf. Section 8 of the Nature Diversity Act).

B. Primary and secondary processes are assessed separately. See Key 1 in Chapter 10.2.

C. The absence of acute damage is not equated with good condition. Sub-lethal processes can be present without visible fractures (Weinnig et al., 2020). Confirmed empirically by Dunlop et al. (2026): LMS and transcriptomic analyses show cellular stress where the visual condition is normal.

D. Damage is assessed in a spatial and temporal context.

E. Cumulative effects are prioritised in cases of uncertainty.

F. Cause is not established without supporting data.

G. Measures are considered before irreversible thresholds are exceeded (cf. Section 9 of the Nature Diversity Act and Key 5).

12. Cumulative effects and non-linear progression

12.1 Conceptual progression model for damage development

1. Healthy colony – Active polyp filtration and intact structure.

2. Physiological stress – Reduced energy balance.

3. Reduced polyp activity – Periodic retraction.

4. Sediment accumulation – Increased particle binding.

5. Secondary colonisation – Epibionts become established.

6. Advanced smothering – Extensive overgrowth.

7. Indicative habitat collapse – Indicative structural breakdown.

Early stages (1–3) can be reversible. Later stages are considered practically irreversible on a management timescale (Roberts et al., 2006).

12.2 Particularly critical stressor interactions

Temperature × organic loading: Increased metabolic demand + reduced capacity to cope.

Organic loading × reduced current/oxygen: Local oxygen reduction.

Sediment × nutritional stress: Intensified sediment-related impact on weakened colonies.

Organic loading × pharmaceuticals: Delousing agents as an additional stressor (Dunlop et al., 2026).

12.3 Hydrodynamic modelling and actual areas of impact

VDWS Transition (Dunlop et al., 2026) documents that a simple distance measurement is insufficient. Current direction means that downstream areas can receive higher sedimentation than nearer areas outside the main current direction.

The framework recommends a shift from distance-based buffer zones to site-specific assessments based on high-resolution hydrodynamic modelling. b-MBI may be used as a supplementary indicator under development, but it has not been regionally validated for Norwegian conditions and cannot on its own verify an impact gradient (IMR 2026-14).

May be relevant to Section 10 of the Nature Diversity Act and, where the decision concerns technique, method of operation or siting, Section 12.

13. Relationship to Sections 4, 5 and 8–12 of the Nature Diversity Act

The framework distinguishes between a core technical basis in Sections 4, 5 and 8–10 of the Nature Diversity Act and a measure-dependent anchoring in Sections 11 and 12. The principles in Sections 8–12 are applied as guidelines in the exercise of public authority, cf. Section 7, and the assessment must appear in the decision. The framework provides the technical basis; the competent management authority makes the final legal assessment.

The Nature Diversity Act	Relevant chapters	Relevance to decisions
Section 4 of the Nature Diversity Act – Management objectives for habitat types and ecosystems	Chapters 1–7, 10	Links types of damage and severity to the condition of the habitat types and ecosystems to be managed.
Section 5 of the Nature Diversity Act – Management objectives for species	Chapters 6, 6.4, 10	The classification of mechanism, severity and reversibility supports the assessment of the population status and trend of the species.
Section 7 of the Nature Diversity Act – Principles for official decision-making in Sections 8–12	Chapter 13	The principles in Sections 8–12 of the Nature Diversity Act are applied as guidelines in the exercise of public authority; the assessment must appear in the decision.
Section 8 of the Nature Diversity Act – The knowledge base	Chapters 1–7, 10, 11	Systematises species condition and damage mechanisms. The keys in Chapter 10 provide a verifiable classification.
Section 9 of the Nature Diversity Act – The precautionary principle	Chapters 8, 10.6 (Key 5), 11.7	T1 can provide decision support where Section 9 of the Nature Diversity Act is relevant following a specific assessment (high grade and low reversibility).
Section 10 of the Nature Diversity Act – The ecosystem approach and cumulative environmental effects	Chapter 10.6 (T3), Chapter 12	Measure category T3 addresses cumulative effects explicitly.

The Nature Diversity Act	Relevant chapters	Relevance to decisions
Section 11 of the Nature Diversity Act – The operator bears the costs of environmental degradation	Chapters 7, 9, 10.6 (T2)	Relevant only where an identifiable operator and cost liability can be assessed under relevant legislation; the classification code then provides a structured basis for assessing extent. Section 11 of the Nature Diversity Act is not an independent legal basis; cost allocation must rest on other relevant legislation or decision authority.
Section 12 of the Nature Diversity Act – Environmentally sound techniques and methods of operation	Chapters 7, 10.6 (T1–T2), 12.3	Relevant where a measure concerns the choice of technique, method of operation or siting; identifies vulnerability factors and alternatives that limit damage.

Section 8 of the Nature Diversity Act – The knowledge base: The framework systematises types of damage, structures field observations and links them to the literature. The keys in Chapter 10 facilitate a more verifiable classification.

Section 9 of the Nature Diversity Act – The precautionary principle: The framework makes sub-lethal processes visible. Section 9 is assessed specifically where the knowledge base is insufficient and the damage potential makes the provision relevant; T1 can provide decision support in such cases.

Section 10 of the Nature Diversity Act – The ecosystem approach and cumulative environmental effects: The framework describes cumulative effects and measure category T3, dedicated to cumulative loading.

Section 11 of the Nature Diversity Act – The operator bears the costs of environmental degradation: Relevant only where an identifiable operator and cost liability can be assessed under relevant legislation. The framework does not determine cost liability.

Section 12 of the Nature Diversity Act – Environmentally sound techniques and methods of operation: Relevant where a specific measure concerns the choice of technique, method of operation or siting; the framework identifies critical impacts and alternative sitings.

14. Limitations

- The framework is not statistically validated.
- Thresholds are operational and indicative, not biologically absolute.
- The keys in Chapter 10 require systematic field documentation.
- Establishing cause requires supplementary data.

- The reference basis is focused on a limited selection of key works on cold-water corals, Norwegian waters and aquaculture-related impact. The classification keys, thresholds and measure categories are built on this focused basis, not on a systematic literature review. A broader grounding in the literature should be sought in further development.
- Transferability between species is limited. Even though the core mechanisms are process-based, Chapter 6.4 shows that sensitivity varies substantially between species and that certainty is low for several species. The same diagnostic logic does not apply equally well to all species.
- The keys and measure categories are decision support, not a decision engine. The management objectives in Sections 4 and 5 of the Nature Diversity Act and the principles in Sections 8–12, cf. Section 7, must be assessed specifically in the individual case.

15. Example of technical wording for the decision basis

Based on systematic classification in accordance with Chapter 10, the observation is assessed as most consistent with code E-II-2-R3a-T2: sediment-induced damage with organic enrichment, moderate grade, consistent mechanism (basic), partially reversible, active measures should be considered. Alternative explanations cannot be fully ruled out without supplementary data.

Even though a direct causal relationship cannot be established without supplementary analyses, Section 9 of the Nature Diversity Act must be assessed specifically where the knowledge base is considered insufficient and the damage potential meets the conditions, before practically irreversible thresholds are exceeded.

The available information is not sufficient to grade cumulative loading. Prior, ongoing and expected impacts must be assessed specifically under Section 10 of the Nature Diversity Act. The classification is decision support and does not replace ordinary administrative discretion.

16. Further development

16.1 General areas for development

- A standardised visual scoring protocol
- Inter-calibration between observers
- Integration of hydrodynamic data
- Quantitative modelling of progression
- Further validation of the b-MBI index for Norwegian waters
- AI-based image analysis for standardised LMS interpretation
- Empirical validation and calibration of the keys in Chapter 10 against additional datasets

- Digital implementation of the keys as a field-based decision-support app

16.2 Roadmap towards calibrated status

In its present form, the framework is not calibrated against a standardised reference dataset. This chapter specifies concrete milestones that must be achieved before the framework can change status from an 'operational decision-support tool' to a 'calibrated framework'. The roadmap is organised in three dimensions and provides a concrete basis for collaboration with IMR, NINA, the Norwegian Environment Agency and other institutional actors.

The requirements for the number of sites, seasons, observations and years given below are proposed planning criteria, not established professional standards.

Dimension 1 – Underlying data

- **D1. Standardised reference dataset:** The establishment of a documented dataset with field observations from at least 5 geographically dispersed sites, across at least 2 seasons, with systematic photo documentation following a fixed protocol.
- **D2. Environmental parameters linked:** Each observation in the reference dataset linked to modelled sedimentation, measured O_2, TOC and current data.
- **D3. Time series established:** Repeated observations from the same fixed measurement points, a minimum of 3 time points per site.
- **D4. Species-specific coverage:** Sufficient underlying data for at least 3 of the species in Chapter 6.4, with at least 30 individuals per species.

Dimension 2 – Methodological validation

- **M1. Inter-calibration:** At least 3 independent observers classify the same dataset. Target: Fleiss' kappa ≥ 0.7 for Key 1 (damage mechanism) and weighted kappa ≥ 0.6 for Key 2 (damage severity, ordinal). For two observers, Cohen's kappa is used.
- **M2. Threshold validation:** Statistical testing of the % intervals in Key 2 (30%, 70%, 85%) against measured biological endpoints. R^2 alone does not validate the classification thresholds; use biological endpoints with e.g. sensitivity, specificity and ordinal/logistic modelling.
- **M3. Validation of sediment thresholds:** Empirical testing of the indicative levels (> 1000 and > 2000 g/m², accumulated over two years; study- and site-specific reference levels) against observed health effects in independent datasets.
- **M4. Independent field validation:** The keys applied to a dataset outside the development basis, against an independent reference classification (predefined expert consensus). Target: balanced accuracy, sensitivity/specificity or macro-F1; overall accuracy alone can mask poor classification of rare categories.
- **M5. Sensitivity analysis:** Quantification of how robust the classification is to minor variations in observations (e.g. ± 5% damage grade).

Dimension 3 – Institutional anchoring

- **I1. Peer review:** Publication of the method in a peer-reviewed scientific journal, preferably international.

- **I2. Consultation with institutional actors:** A formal review and comment round with IMR, NINA, the Norwegian Environment Agency and the relevant County Governors.
- **I3. Integration with existing protocols:** A compatibility assessment against MAREANO, OSPAR thematic assessments (OSPAR, 2023) and other established monitoring systems.
- **I4. Training material:** The development of a standardised training package (manual, photo references, exercise set) for consistent application.

Operational criteria for calibrated status

The framework can change its status to 'calibrated' when the following minimum criteria have been met:

Criterion	Milestones achieved	Operational threshold
Underlying data	D1 + D2 + D3	At least 5 sites, 2 seasons, linked environmental data
Inter-calibration	M1	Fleiss' kappa ≥ 0.7 for Key 1
Threshold validation	M2 + M3	Predefined biological or classification-based endpoints with relevant measures (sensitivity, specificity, balanced accuracy, observer agreement)
Independent validation	M4	Satisfactory balanced accuracy / macro-F1 on an external dataset
Institutional anchoring	I1 + I2	Peer review + consultation completed

Gradual progression: The framework can achieve a defined internal development status through the stepwise attainment of the criteria. It is recommended that the level of calibration be reported explicitly in all future revisions, e.g. as 'internal development status: D1+D2+M1 achieved'.

Preliminary planning estimate: Full calibration against all criteria is assessed to require 3–5 years of coordinated effort with sufficient funding and institutional collaboration. Internal development status (D1+M1+M2) can be achieved within 1–2 years through targeted effort.

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Types of damage in cold-water corals – technical framework (Rev. 2.4)

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