Napital

In collaboration with: AECOM CMA TESTING

# The Natural Capital Index White Paper

## From Method to Market: A Transparent Methodology for Verifiable Nature Recovery

Version 1.0

# Foreword

In 2024, Napital—as the principal initiator—joined with AECOM to set out the strategic case for natural capital as a new infrastructure class in The Natural Capital Manifesto. That document established why nature recovery should be treated with the same investment discipline as any other infrastructure asset. This white paper takes the next step: it explains how.

The Natural Capital Index (NCi) is the verified ecological performance metric that realise the manifesto's vision. Conceived and driven forward by Napital, with AECOM as technical lead and independent verification provided by CMA Testing, the NCi translates restoration outcomes into a consistent, comparable and auditable set of performance data. It is the instrument through which natural capital becomes investable.

This paper sets out the methodology in full. It describes the conceptual architecture of the index, the technical basis for each of its five components, the data collection and analytical approaches behind them, and the way they combine to track change over time. The Pulau Bintan NCi Pilot in Indonesia is used throughout as a worked example, including a candid account of where the pilot context necessitated methodological compromises. Transparency about constraints is, we believe, a precondition for trust, and trust is a precondition for finance.

# Chapter 1

## Why a Natural Capital Index

Carbon markets exist because the world agreed on a single, traceable unit of measurement: the tonne of carbon dioxide equivalent. Nature has had no such equivalent. Restoration outcomes have been described qualitatively, measured inconsistently, and reported in formats that resist comparison.

Despite this, the Taskforce on Nature-related Financial Disclosures (TNFD) has adapted the United Nations System of Environmental-Economic Accounting — Ecosystem Accounting (SEEA EA) concept of Ecosystem Condition, which describes. Both frameworks describe ecosystem condition through the three dimensions of composition, structure and function (TNFD, 2026), providing an approach which can be applied across any ecosystem type. Whilst this outlines a high-level approach, what it does not provide is a measurement protocol, a way to actually generate the numbers that those frameworks anticipate, which can be used at scale across a diverse plethora of habitat restoration projects.

The NCi fills that gap. It applies the composition–structure–function typology as a measurement scaffold, defines the data inputs and analytical methods for each dimension, and produces a set of performance values that can be baselined, projected, monitored, verified and ultimately monetised. It is designed to be defensible to ecologists, intelligible to investors, and auditable by independent third parties.

We also see the index as akin to a living organism, evolving over time through improved iterations as innovative assessment methods, new technology, and new reference data come to the forefront. What is presented in this document is the starting point.

**A tiered approach.** The NCi is designed to be adopted in three tiers of increasing data completeness, each producing useful and verifiable outputs within its own scope. The tiers reflect the practical reality that the field data and reference infrastructure required for the full methodology, particularly the eDNA and bioacoustic data streams that support the compositional biodiversity metrics, is still maturing in many project geographies. Rather than defer adoption until every input is available everywhere, the NCi defines earlier tiers that let projects mobilise with the data they can collect today and advance as capability develops.

**Terrestrial for now; freshwater and coastal in future versions.** Whilst there are future plans to broaden the NCi methodology out to cover freshwater and coastal ecosystems, the current version of the NCi methodology is specified for terrestrial ecosystems and biodiversity only. The five metrics, the biodiversity accounting basis of Metric 1, the eDNA and bioacoustic protocols of Metrics 2 and 3, and the four ecosystem-service methods are all developed and calibrated for terrestrial ecosystems, with the Pulau Bintan Pilot situated in tropical secondary forest. Freshwater and coastal habitats, and the biodiversity and ecosystem services they support, are not covered by this version. Extensions of the methodology to these habitat types are on the roadmap for future development, and will be released as separate versions. Projects intending to apply the NCi to sites containing freshwater or coastal components should, in the interim, report on the terrestrial portion using this methodology and treat the aquatic components separately using established sector-specific methods.

# Chapter 2

## Anatomy of the Natural Capital Index

The NCi measures five things about a recovering ecosystem: its biodiversity, and its capacity to store carbon, remove air pollution, regulate water, and build healthy soil. Each is scored on a simple 0-to-1 scale, where higher is better and the benchmark is a healthy, relatively undisturbed example of the same habitat nearby, the "reference site." We predict where each score should reach over a thirty-year restoration period, then measure progress over time to check that recovery is on track. The five scores are reported individually, and also combined into a single overall score for headline reporting. Everything that follows is an elaboration of these five measurements, how they are measured, and how they are combined.


Figure 1. The 'Core 5' of the Natural Capital Index: the five performance domains measured for every recovering ecosystem, comprising Biodiversity alongside four ecosystem-service capacities (Water Regulation, Soil Quality Regulation, Air Quality Regulation, and Carbon Storage).

### Anchored in Ecosystem Condition

The NCi is built on the ecosystem condition framing established by the UN SEEA EA and adopted by TNFD (UN, 2021; TNFD, 2026). Ecosystem condition is described through three components:

- **Composition** — the species and biological communities that make up the ecosystem, including their diversity, abundance and identity.
- **Structure** — the physical arrangement of the ecosystem, including habitat type, vegetation layering, biomass distribution and successional stage.
- **Function** — the ecological processes the ecosystem performs, including carbon stocks, water regulation, soil formation and air filtration.

The added benefit of aligning with these definitions is that any organisation undertaking nature-related disclosures can readily utilise or integrate the NCi approach.

The NCi assigns specific measurement approaches to each dimension and combines them into two index metrics: a Composite Biodiversity Index (predominantly composition and structure) and four selected ecosystem service metrics (drawn from function). Together these form the headline Index Score.

**The habitat parcel as the unit of measurement.** The NCi applies its measurement framework at the level of the habitat parcel, the operational unit at which each metric is measured, scored and reported. A habitat parcel is a discrete area of consistent habitat type and management within a project site, defined at baseline. Habitat parcels may be subdivided to consider the ecological condition of a particular habitat type; in some cases, a single habitat type may be subdivided into different parcels to reflect the ecosystem of 'habitat' condition. Parcel-level results are aggregated to give site-level and project-level outputs. The parcel is the level at which the composition, structure and function of the ecosystem are observed together. This is also from which the different ecosystem service metrics are derived from. All five NCi metrics are therefore measured, scored and normalised at parcel level before aggregation. This ensures that within-site heterogeneity, for example a project containing both intact forest fragments and heavily degraded parcels, are accounted for.

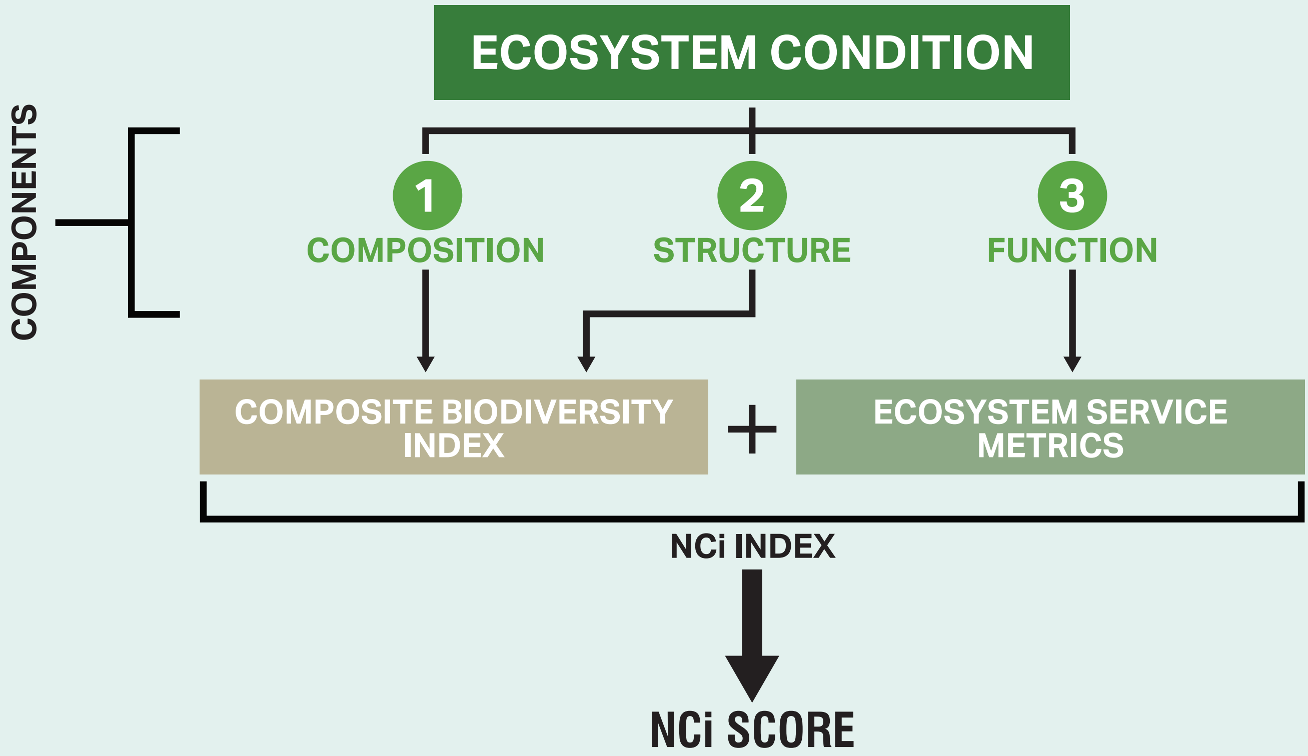



Figure 2. Conceptual architecture of the Natural Capital Index (NCi). Ecosystem condition is assessed across three components (composition, structure, and function) which together inform two index elements: the Composite Biodiversity Index and Ecosystem Service Metrics. These are combined to produce the NCi Score.

# The NCi Architecture

### Individual Ecosystem Service Performance Scores

The NCi is the integrated metric through which natural capital recovery is measured, monitored and reported. It is structured as two reporting outputs. The first is the set of five individual performance scores, one for each metric (biodiversity, air, water, soil and carbon), and under the Tier 1+ and Tier 2 approaches outlined in the following section, normalised to a 0–1 scale.

Reported together as an ordered set, these five scores are referred to as individual ecosystem service performance scores. Each metric is measured independently, normalised to its appropriate benchmark, tracked over time, and verified separately. The individual performance scores are the methodologically primary layer: it preserves the diagnostic detail that distinguishes a balanced recovery from a partial one, and it makes the source data inspectable to any user.

### The Composite NCi Score

The second output is the Composite NCi Score, a single 0–1 scalar derived from the individual performance scores for headline reporting, finance applications, and yearonyear tracking. Whilst this is not a requirement of the Tier 1 (foundational) assessment phase, it is a requirement of the Tier 1+ (standard) and Tier 2 (comprehensive) data collection and analysis phases.

The Composite Score is calculated as the geometric mean of the five normalised metrics[1]. In simple terms, the geometric mean is a way of averaging that rewards balanced progress and penalises neglect of any single ecosystem service performance: a project cannot earn a high overall score by maximising carbon while letting biodiversity stagnate. It has three desirable properties: the output remains on the same 0–1 scale as the inputs, it penalises imbalance between metrics, and it collapses to zero only in the genuine case where any single metric is itself zero.

$$\text{Composite NCi Score} = \sqrt[5]{B \times A \times W \times S \times C}$$

B = Composite Biodiversity Index
A = Air Quality Metric
W = Water Regulation Metric
S = Soil Quality Metric
C = Carbon Stock Metric

Where B, A, W, S and C are the normalised (0–1) scores for biodiversity, air, water, soil and carbon respectively. A worked example: a site scoring 0.5 across all five metrics returns a Composite Score of 0.5. A site scoring 0.8 on four metrics and 0.2 on one returns 0.61, penalised relative to the arithmetic mean of 0.68 because the imbalance is real, but not collapsed to zero because four of five metrics are performing well.

The two reporting outputs serve different audiences. Theindividual performance scores arewhat verifiers, ecologists and site managers work with, it shows where recovery is on track and where it is lagging, parameter by parameter. The Composite Score is what investors, corporate reporters and the public engage with, it gives a single number to track from baseline through restoration. Neither layer displaces the other. Both are reported alongside one another at every monitoring cycle.

[1]The geometric mean is the standard compositing approach for normalised environmental and development indices internationally. The UN Human Development Index moved to the geometric mean in 2010 specifically to penalise imbalance between its constituent dimensions. The methodological precedent is well established.

## A Phased Assessment Model

A comprehensive NCi assessment requires a substantial body of field data: habitat and vegetation surveys, soil sampling, environmental DNA (eDNA) laboratory analysis, bioacoustic deployment, and the ecosystem service inputs that sit alongside them. Collecting all of this in its complete form is necessary for the methodologically comprehensive expression of the index, but two practical realities sit alongside that ambition:

1. The data and reference infrastructure on which the methodology depends, particularly eDNA reference libraries and paired bioacoustic reference recordings for many ecoregions, is still maturing, and not every project geography currently supports the full configuration.
2. Projects mobilise on different timelines, and locking in the preintervention habitat baseline cannot be made conditional on the slowest of the input streams being available. The methodology therefore defines two assessment tiers of increasing data completeness, each producing useful and verifiable outputs within its own scope, and structured so that data collected at a lower tier remains compatible with, and can be supplemented to reach, the higher tiers. Tier 2 (Comprehensive) is the recommended configuration where the underlying data and reference infrastructure allows, and is the form to which projects are encouraged to advance.

**Tier 1 (Foundational).** Tier 1 establishes and tracks the five NCi metrics (biodiversity, air, water, soil and carbon) in their absolute physical units, reported and monitored independently as individual ecosystem service performance scores.

Under Tier 1, these scores are not combined into a Composite NCi Score.

As this is a foundational approach, only the following metrics are utilised:

- Biodiversity - Metric 1: Habitats, Vegetation and Structural Diversity
- The Soil Index
- The Water Index
- The Air Index
- Carbon Stock

The habitat and vegetation biodiversity accounting metric (Metric 1) provides the structuralvegetative line of evidence for the biodiversity component and, as the predictive engine for the wider index, supports literaturebased projections for the four ecosystem services derived from the projected habitat composition. The additional biodiversity metrics which make up the Composite Biodiversity Index, are not required to be undertaken for a Tier 1 phased approach.

Additionally, the four ecosystem service metrics are measured and reported in their native units (tonnes of carbon, kilograms of $PM_{2.5}$ removed per year, percentage soil organic matter, and the water composite index value). Tier 1 is the entry point through which a project can be mobilised and through which absolute-unit performance can be tracked against parcel-specific targets, without requiring the project to commit to normalisation parameters or the Composite NCi Score framework at the outset.

Tier 1 is a legitimate methodology in its own right, not a shortcut. It rests on five measured datasets and the most established and independently auditable of the biodiversity methods, used on their own rather than as weak proxies. It captures the one baseline whose preintervention timing is integritycritical (the Metric 1 habitat baseline), so the timesensitive measurement is never the one deferred. And it reports in absolute, inspectable units that finance reviewers, regulators and verifiers can engage with directly.

What Tier 1 does not produce is a Composite NCi Score: that requires the normalisation framework formalised at Tier 1+ and the verified fieldmeasured biodiversity composition data formalised at Tier 2.

**When Tier 1 is the appropriate entry point.** A project would adopt Tier 1 as its starting tier wherever absoluteunit reporting against parcelspecific targets is the appropriate frame, or where the normalisation parameters required for the Composite NCi Score cannot yet be confidently set. Four situations are typical:

- Site selection and prioritisation: where a developer holding several candidate sites uses Tier 1 to characterise them in absolute units, and commits the further data collection required to advance to Tier 1+ or Tier 2 only to the sites that proceed, rather than committing the full programme everywhere at once.
- Project development and preliminary investment decisions: where absoluteunit performance is the appropriate basis for earlystage decisions and the Composite NCi Score framework is being built up over the project's first reporting cycles.
- Feasibility assessment and intervention design: where the biodiversity accounting metric is used to model the successional trajectory and compare restoration options against absolute outcomes before a design and its associated field programme are fixed.
- Seasonal or logistical constraints: where the Tier 2 compositional biodiversity data (bioacoustic deployments or eDNA sampling) cannot be collected immediately. Tier 1 allows the project to proceed and to lock in the preintervention habitat baseline on time, with the compositional metrics added later as conditions permit.

**Tier 1+ (Standard).** Tier 1+ takes the same five metrics measured at Tier 1 and applies the NCi normalisation framework to them. Each of the five metrics is normalised to its appropriate benchmark on the 0–1 scale (progresstotarget for the four ecosystem services and the habitat-and-vegetation biodiversity metric; referencestate similarity for the compositional biodiversity metrics when introduced at Tier 2), producing the NCi individual performance scores. The five normalised values are then combined through the geometric mean to produce the Composite NCi Score. Tier 1+ is the minimum tier at which a verified Composite NCi Score can be issued. At this tier the biodiversity component of the index is represented solely by the structuralvegetative line of evidence (Metric 1); the soil biota and faunal acoustic composition metrics that complete the threecompartment biodiversity stratification are added at Tier 2.

**Tier 2 (Comprehensive).** Tier 2 takes Tier 1+ and adds the two compositional biodiversity metrics effectively adopting the full NCi approach:

1. Biodiversity – Metric 2: Soil Biota Community Composition
2. Biodiversity – Metric 3: Fauna Species Diversity

With these in place, the Composite Biodiversity Index is generated from all three biodiversity sub-metrics rather than from Biodiversity Metric 1 alone, and the biodiversity component captures all three of its intended compartments: the structural and vegetative (Metric 1), the below-ground (Metric 2), and the above-ground vocalising fauna (Metric 3).

Tier 2 produces the full NCi individual performance scores and Composite NCi Score, and is the configuration recommended where data and reference infrastructure allows. It is also the configuration to which Tier 1 and Tier 1+ projects are intended to advance as that infrastructure matures.

**Why Tier 2 is the recommended configuration.** Tier 1 produces useful absolute-unit data but no integrated score; Tier 1+ produces the integrated score from one biodiversity sub-metric and the four ecosystem services. Only Tier 2 measures all three biodiversity compartments, structural-vegetative, below-ground, and above-ground vocalising fauna, that the methodology is designed to integrate. It is also where the diagnostic value of the biodiversity component is fully realised: a habitat-and-vegetation metric on its own captures the structural recovery of a parcel but tells us very little about whether the soil community and the soundscape are following.

Biodiversity Metrics 1 and 2 report on parts of the biodiversity recovery that the habitat metric is silent on, and divergence between the three is itself an ecological signal worth capturing. For these reasons Tier 2 is the recommended target configuration, and projects starting at Tier 1 or Tier 1+ are encouraged to advance to Tier 2 as data and reference infrastructure permits.

**Baseline integrity and timing.** A single rule governs the timing of data collection across the three tiers, and it follows directly from how each metric is normalised. The habitat and vegetation biodiversity metric (Metric 1) is normalised as progress toward a parcel-specific target, so its baseline is a point-in-time measurement of the pre-intervention condition. This baseline must therefore be established before any intervention begins on a parcel; a Metric 1 baseline taken after works have started would potentially understate the degraded starting condition and potentially alter the apparent uplift, and is not permissible.

The remaining four ecosystem-service metrics, together with the two compositional biodiversity metrics (Biodiversity Metric 2 and 3, both of which are benchmarked against a climax or ideal reference state rather than a parcel-specific target – see 'Restoration Projection'), are benchmarked against the reference site rather than a point-in-time baseline. Their benchmark, the ecosystem or habitat's 'reference state', does not change over time, so their field data may be collected at any tier and at any point along the restoration trajectory without compromising integrity: a later measurement is simply a point further along the trajectory toward the reference state, not a corrupted baseline. This has a specific consequence for projects that begin at Tier 1 or Tier 1+ and later advance to Tier 2.

The Metric 2 and Metric 3 datasets introduced at the point of upgrade do not corrupt the baseline of the project, because they are reference-anchored rather than time-anchored, and they enter the index reading the parcel's position on its trajectory toward the climax reference at the moment of first measurement. Where this occurs, the date of first measurement for each metric must be recorded and disclosed, so that the position of each measurement on the restoration trajectory is transparent. This latitude applies only to the reference-benchmarked metrics; the Metric 1 habitat baseline remains the one measurement whose pre-intervention timing is mandatory, and which Tier 1 is structured to capture from the outset.

## Restoration Projection: Assessing Progress to Target Condition, Reference Sites and Normalisation

Every score in the NCi is expressed on a 0–1 scale, but the benchmark that defines "1" is chosen to suit the type of data being measured. Two normalisation modes are used, and the distinction is deliberate.

**Progress-to-target normalisation.** It applies to metrics that are absolute physical quantities for which a realistic target value can be computed: carbon stock, soil organic matter, water regulation, air quality (particulate removal), and the habitat-and-vegetation biodiversity metric. For these, each parcel is scored as its current value divided by the value it is projected to reach at its restoration target, so the score rises toward 1 as the parcel approaches its own realistic restoration goal. The target is parcel-specific: a scrubland parcel is scored against its young-secondary-forest target, not against a distant climax state it is not expected to reach within the restoration period.

**Progress to reference-site-state normalisation.** It applies to metrics that have no computable target value and can only be expressed as similarity to an observed natural state (i.e., an ideal, 'pristine' or climax community reference site). This covers the two compositional biodiversity metrics: soil biota community composition (eDNA) and faunal species diversity (bioacoustics). For these, each parcel is scored against a paired reference site representing the relatively undisturbed climax habitat for the ecoregion. There is no meaningful way to specify, in advance, the "target" soil microbial community or the "target" soundscape of a recovering parcel; one can only measure how closely it resembles a real, healthy reference. The score rises toward 1 as the parcel's community composition or soundscape converges on that of the reference site.

Both modes yield a 0–1 score and both feed the same geometric-mean composite. They differ only in what "1" represents: attainment of the parcel's restoration target in the first case, equivalence to the climax reference state in the second.

**Defining a reference site.** The reference site itself is defined once for a project: a nearby, relatively undisturbed example of the climax habitat for the ecoregion (in the Bintan pilot, lowland dipterocarp forest in Good condition). It serves two functions: it provides the similarity benchmark for the compositional metrics, and it defines the theoretical ceiling that informs what realistic restoration targets look like for the progress-to-target metrics. Where no suitable reference site is available on site and no open-source reference data exists, a reference site must be sampled directly as part of baseline characterisation.

**Why two modes.** The two normalisation modes exist because the two categories of metric they apply to are fundamentally different kinds of measurement. The four ecosystem services and the habitat-and-vegetation biodiversity metric have computable target values: it is possible to specify what carbon stock, $PM_{2.5}$ removal, soil organic matter, water composite value or biodiversity units the parcel should reach at restoration. For these, progress-to-target normalisation is therefore used. On the other hand, the two compositional biodiversity metrics do not have computable target values: currently there is no principled way to specify in advance what the 'target' soil microbial community or 'target' soundscape should look like. For these, the only defensible normalisation is similarity to an observed healthy reference state. Forcing both categories into a single mode would require either specifying target community compositions that lack empirical grounding, or reframing physical quantities like carbon stock as if they had no target, both of which would be methodologically weaker than accepting the two-mode structure. Users of the Composite NCi Score should interpret it as a hybrid on this basis.

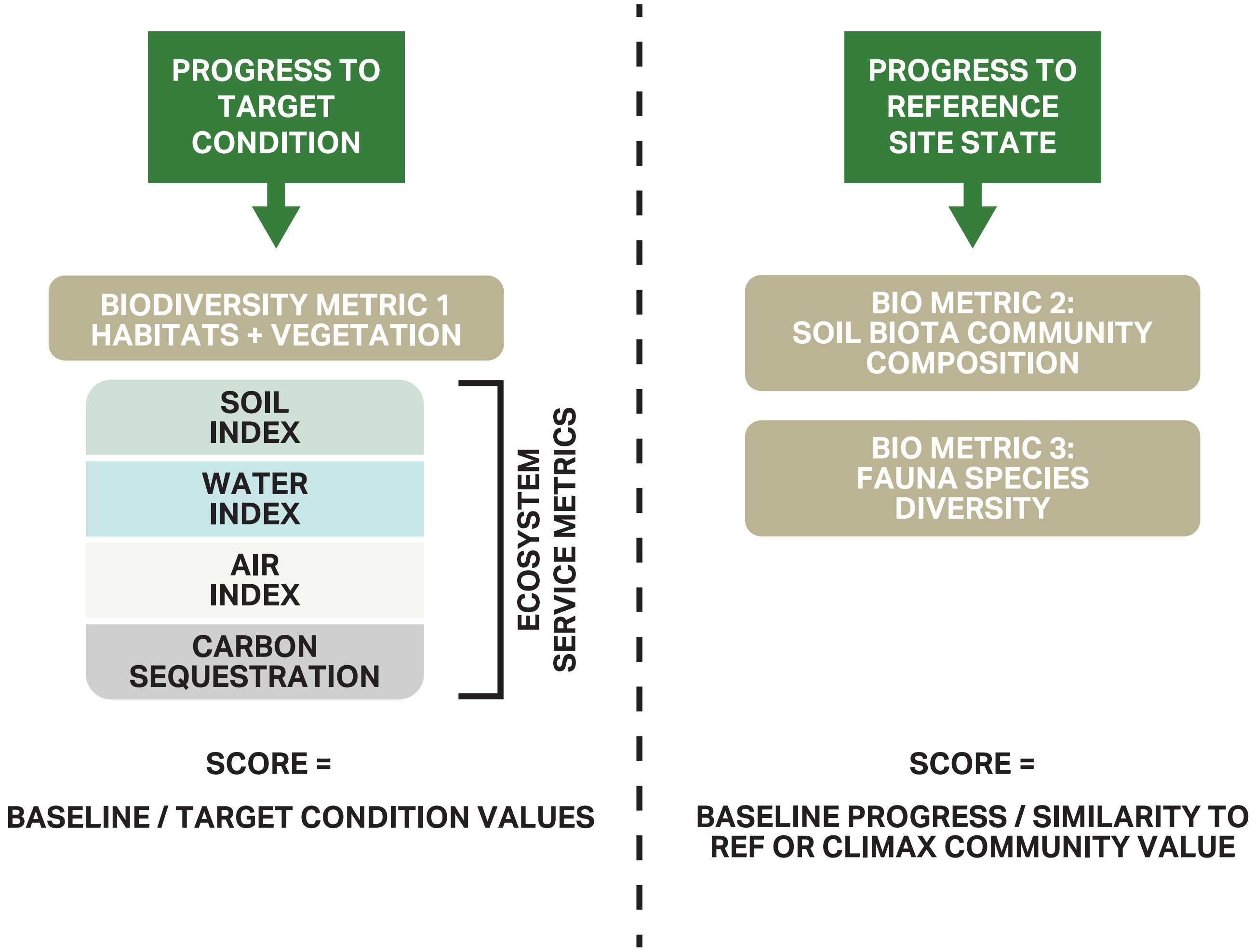



Figure 3. NCi metric architecture and scoring basis. Left: Tier 1 metrics, comprising Biodiversity Metric 1 (Habitats and Vegetation) and four Ecosystem Service Metrics (Soil, Water, Air, and Carbon Sequestration), scored as baseline progress toward target condition values. Right: Tier 2 compositional biodiversity metrics — Bio Metric 2 (Soil Biota Community Composition) and Bio Metric 3 (Fauna Species Diversity) — scored as baseline progress relative to a reference site state.

# Chapter 3

## Composite Biodiversity Index Component

Biodiversity is the most difficult of the five parameters to measure consistently. It is multidimensional, naturally variable, and resistant to single-figure summary. The NCi addresses this by drawing on three complementary components of an ecological habitat (one each for habitat condition, soil biota and aboveground faunal species diversity) and combining them through a transparent weighting scheme.

### Terrestrial Ecosystems: Design Principles

The three aforementioned components address three constraints that any practical biodiversity measurement system must satisfy: it must cover the diversity that actually exists, it must be implementable at scale, and it must produce data that can be standardised, verified and tracked over time.

Terrestrial biodiversity is not distributed uniformly. It exists in three broadly distinct compartments: the structural and vegetative (habitat type, canopy structure, floral composition), the below-ground (soil microbial communities, fungi, soil invertebrates), and the above-ground mobile fauna (birds, mammals, herpetofauna, invertebrates). Whilst each compartment interacts with one another, each behaves differently during ecosystem recovery, and each requires a different measurement approach. A biodiversity metric that captures only one compartment, as the majority of conventional metrics do, produces an incomplete picture of recovery.

The NCi's biodiversity component is therefore stratified across these three compartments. For each compartment, the most appropriate scalable method has been selected:

- **The structural and vegetative compartment** is addressed through a region-specific biodiversity accounting approach, which captures habitat distinctiveness, structural diversity, vegetation composition and condition.
- **The below-ground compartment** is addressed using environmental DNA (eDNA), which captures soil microbial community composition (e.g., bacteria, fungi etc.) at a level of taxonomic resolution that would be impossible through conventional sampling.
- **The above-ground faunal compartment** is addressed through bioacoustic monitoring, which captures the soundscape produced by vocalising fauna as a proxy for above-ground animal diversity.

Each method utilises a form of nature tech: modern, scalable, technology-enabled measurement that produces standardisable data outputs suitable for digital monitoring and third-party verification. This is a deliberate constraint. The NCi is designed so that it can be deployed across hundreds or thousands of hectares, by trained field teams rather than resident taxonomists, with outputs that flow into a digital twin and are accessible for independent audit.

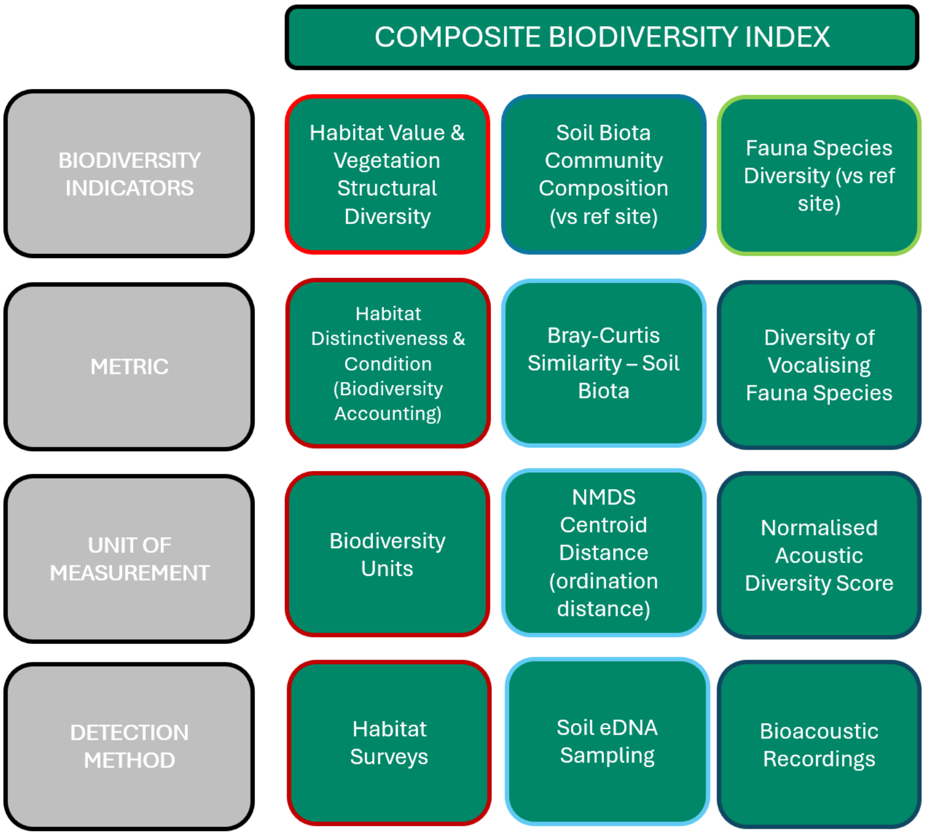



Figure 4. Composite Biodiversity Index structure, showing the three biodiversity indicators assessed under the NCi — Habitat Value and Vegetation Structural Diversity (Tier 1), Soil Biota Community Composition (Tier 2), and Fauna Species Diversity (Tier 2) — with corresponding metrics, units of measurement, and detection methods.

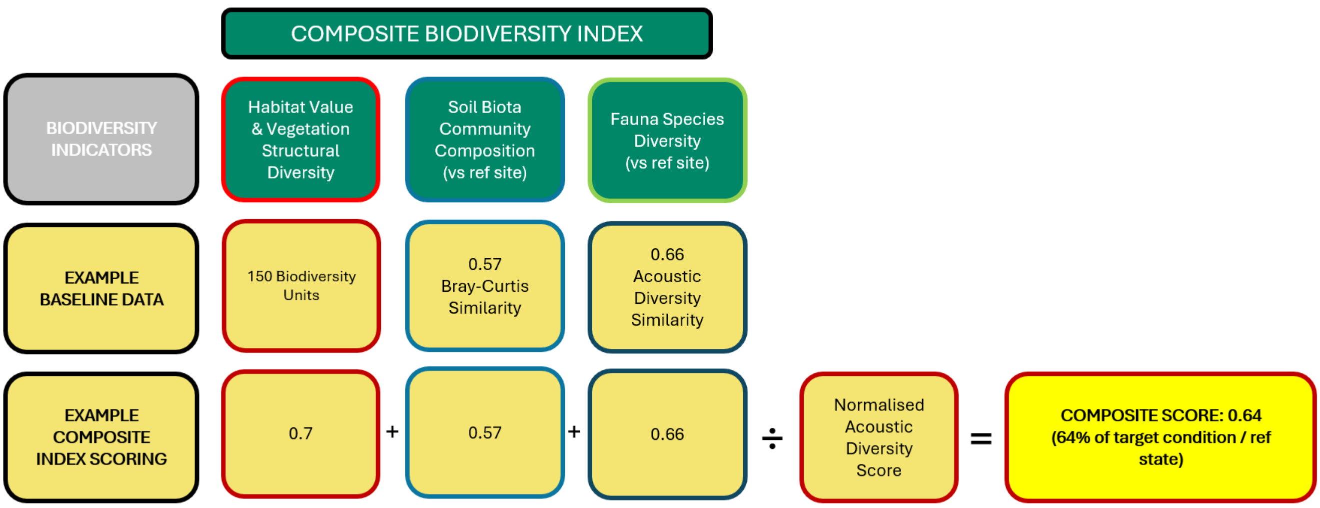



Figure 5. Composite Biodiversity Index structure and illustrative scoring, showing the three biodiversity indicators — Habitat Value and Vegetation Structural Diversity (Tier 1), Change in Soil Biota Communities (Tier 2), and Change in Fauna Community Composition (Tier 2) — with example baseline data, normalised component scores, and derivation of the Composite Biodiversity Index Score as an arithmetic mean. Example values are illustrative only.

## A Systems-based Approach, Not a Species List

The NCi uses a systems-based approach to assessing baselines, projecting restoration, and confirming restoration success through monitoring. It measures whether an ecosystem is functioning and trending toward a defined reference state, not which individual species are present at a given moment. Nonetheless, single-species data remains valuable, and we recommend collecting it alongside the index, through camera trapping, targeted surveys, and conservation-significant species records, to inform site management, regulatory compliance and stakeholder engagement.

For example, in the Napital Bintan NCi Pilot, this work surfaced IUCN Red List and CITES-listed fauna species on site. These data sit alongside the index; they do not enter the index calculation, which draws on the three stratified metrics only. They can, however, be valuable in determining interventions that aim to enhance or restore habitat for biodiversity, and ensure that interventions are proposed that do not create adverse effects to known fauna species.

Figure 6. Representative camera-trap imagery from the Napital Bintan NCi Pilot. Camera trapping is collected as supporting single-species evidence (informing site management, regulatory compliance and stakeholder engagement) and does not enter the index calculation, which draws on the three stratified biodiversity metrics only.

## Metric 1: Habitats, Vegetation and Structural Diversity

The habitat and vegetation metric quantifies the structural and compositional value of habitats present on site. It requires a region-specific biodiversity accounting metric, such as the Singapore Biodiversity Accounting Metric (SGBA), which has been adapted for the wider Southeast Asian ecoregion. The same underlying logic applies in other geographies through equivalent metrics; the UK statutory biodiversity metric (DEFRA, 2024), for example, follows the same conceptual architecture, as do the habitat-hectares approaches used in Australian frameworks.

**The baseline calculation.** Biodiversity units for an existing habitat parcel are calculated as the product of three terms:

***Biodiversity Units = Area (ha) × Distinctiveness × Condition***

Distinctiveness is the intrinsic biodiversity value of the habitat type, scored against criteria such as species richness, irreplaceability, rarity and unique-species support, each banded (typically High, Medium, Low or Zero). Condition is the quality of the specific parcel relative to the best achievable example of its habitat type, assessed through vegetation composition, structural diversity and degradation criteria.

The projection of restored value distinguishes between two pathways: creation, where a new habitat is established on land of negligible existing value, and enhancement, where an existing habitat is improved toward a higher target type or condition. The two are treated differently because they carry risk in different places.

**Creation.** Where a new habitat is created from negligible existing value (for example, bare ground brought into vegetation), there is no secured baseline to carry forward. The entire projected target value is therefore subject to delivery risk and is discounted by the difficulty of successfully establishing the target habitat (i.e., difficulty multiplier):

$$\text{Created Units} = \text{Area} \times \text{Projected Distinctiveness} \times \text{Projected Condition} \times \text{difficulty multiplier}$$

**Enhancement.** Where an existing habitat is improved, the parcel has an extant baseline value. That baseline is retained in full; only the projected uplift above it carries delivery risk, and only that uplift is discounted:

$$\text{Enhanced Units} = \text{Baseline Units} + (\text{Projected Target Units} - \text{Baseline Units}) \times \text{difficulty multiplier}$$

The principle behind both pathways is the same and is worth stating explicitly, because it is the single most important safeguard against over-claiming: risk multipliers apply to projected uplift only, never to secured baseline value. The baseline is measured and certain, so it is never discounted; the future gain is uncertain, so it is discounted according to how ecologically difficult, slow and uncertain the proposed transition is. The difficulty multiplier (a factor between 0 and 1) is preset for each target habitat type, so that a structurally complex climax habitat (harder, slower, less certain to achieve) is credited proportionately less of its projected uplift than a straightforward condition improvement. When an enhancement is trivially achievable the multiplier approaches 1 and the full target is credited; as difficulty rises the credited uplift falls. Enhanced units can therefore never exceed the projected target, and a parcel never scores below the baseline it already holds.

This is the structure used by the UK DEFRA biodiversity metric (both Metric 3.0 and the Statutory Metric), in which the projected uplift is discounted by a difficulty multiplier and, in the fuller form, a temporal multiplier reflecting the time taken to reach target condition, with an optional strategic-significance multiplier applied to the result (DEFRA, 2024). The NCi methodology adopts the same structure as its suggested approach. A single difficulty multiplier is sufficient; where regional data supports it, a temporal multiplier may be added to reflect that slower transitions deliver value later and less certainly. The fuller generalised form is:

***Enhanced Units = [Baseline + (Target − Baseline) × difficulty × temporal] × strategic significance***

**Normalisation.** For its role within the Composite Biodiversity Index, each parcel's habitat-and-vegetation score is expressed as its current units divided by its projected target units, a progress-to-target score on the 0–1 scale, consistent with the four ecosystem service metrics.

**Using or building a region-specific metric.** The NCi does not mandate a single biodiversity accounting metric. Any metric may be used provided it follows the framework set out above (multiplicative valuation across area, distinctiveness and condition; baseline retained in full; projected uplift discounted by appropriate risk multipliers), and provided it has been independently verified. This keeps the methodology tool-agnostic and deployable across geographies, where the appropriate metric will differ. Where practitioners adapt an existing metric or devise a new one for a region, two structural principles must be consdered regardless of regional calibration:

- Biodiversity value must be treated as a multiplication of habitat area, distinctiveness and condition, for the reasons outlined above.
- Risk multipliers must apply to projected uplift only and never to baseline values.

The specific distinctiveness bandings, condition criteria and difficulty multipliers should be calibrated to regional habitats and, wherever empirical recovery data exists, derived from it rather than from expert judgement alone; a known limitation of first-generation accounting metrics is that their multipliers are often expert-set rather than data-derived, and regional adaptations should aim to improve on this where evidence allows. Inspiration can be taken from global biodiversity accounting metric examples.

The reference state for the metric is, where possible, a regionally appropriate reference habitat type, which represents a climax community or an ideal reference state. In the case of the Pulau Bintan Pilot, which involved forest restoration, lowland dipterocarp forest in good condition, was taken as the reference habitat.

## DISTINCTIVENESS CRITERIA - TERRESTRIAL

| CRITERIA | HIGH (3) | MEDIUM (2) | LOW (1) | ZERO (0) |
|---|---|---|---|---|
| **SPECIES RICHNESS:** the total number of flora (vascular plant) and fauna (bird, butterfly, odonate, amphibian, reptile, mammal) species that can be expected to occur in the habitat, excluding introduced fauna species. | High flora and fauna species richness (900 or more species) | Moderate flora and fauna species richness (600 to 899 species) | Low flora and fauna species richness (300 to 599 species) | Very low flora and fauna species richness (Less than 300 species)) |
| **IRREPLACABILITY:** the difficulty of recreating, or replacing the habitat to its ecologically optimal structure and species composition via human intervention, natural or accelerated succession within 30 years. This also takes into account re-establishing of habitat or ecosystem health, and ecological (biotic and abiotic) dynamics required to establish an effectively functioning habitat. | Impossible to recreate/replace (e.g., lowland dipterocarp primary forest) | Difficult to recreate/replace (e.g., native-dominated secondary forest, coastal forest) | Easy to recreate/replace | Not ideal to recreate/replace for biodiversity |
| **RARITY:** area of a particular habitat type remaining as a percentage of all terrestrial land mass in Singapore.<br><br>For intertidal and marine habitats, this is taken as the proportion of land to sea surface area that the habitat covers across Singapore's total coastal area. | Habitat is rare in Singapore (e.g., lowland dipterocarp primary forest, native-dominated secondary forest, coastal forest, casuarina-dominated forest, grassland, fern-dominated vegetation)(<5%). | Habitat is uncommon in Singapore (e.g., abandoned-land forest, waste woodland, scrubland) (5% to 30%) | Habitat is common Singapore (e.g.,vertical greenery, streetscape, urban park/garden, community farm, commercial farm, golf course, turf, skyrise greenery). (>30%). Habitat types which support <300 species, are asumed to be lowest priority for biodiversity and therefore automatically fall under this | Habitat is ubiquitous in Singapore (e.g., buildings). |
| **UNIQUE SPECIES:** the total number of unique flora (vascular plant) and fauna (bird, butterfly, odonate, amphibian, reptile, mammal) species that can be expected to occur in the habitat. Unique species are those that are not typically found in other habitats. | Supports a high number of unique flora and fauna species (15 or more unique species) | Supports some unique flora and fauna species (10 to 14 unique species) | Supports few unique flora and fauna species (Less than 10 species) | Does not support any unique flora and fauna species |

**Biodiversity Accounting Assessment (Biodiversity Unit Calculation)**

**A - Baseline Habitat Biodiversity Unit**

Habitat Parcel (HA) x Distinctiveness x Habitat Condition

**B - Post-Development Habitat Biodiversity Unit**

Post-development Habitat Parcel (HA) x Post-development Distinctiveness x Post-development Habitat Condition + ( 1 - difficulty of creation/enhancement) x A

**C - Calculating Change in Bio Units**

B - A = Net Change in Units

( B - A ) / A = Unit Change (%)

The SGBA uses the ecological value of the habitats to estimate overall biodiversity value, transforming complex data into quantifiable units.

Each habitat type has been split into several habitat parcels, for which specific restoration actions are recommended based on the type and intensity of the disturbance.

Habitats with the highest potential restoration value are

- Bare soil (0 units/ha)

- Scrubland / Grassland (2 units/ha)

Figure 7. Singapore Biodiversity Accounting Assessment framework for terrestrial habitats, illustrating the distinctiveness criteria matrix (Species Richness, Irreplaceability, Rarity, and Unique Species) used to assign habitat condition scores, and the Biodiversity Unit calculation methodology for baseline and post-development scenarios.

**Data collection.** Metric 1 is built on structured field survey, and the quality of the metric depends directly on the quality of the survey. Two field activities are required at baseline: habitat classification, and habitat-condition assessment.

- Habitat classification. The project site is mapped and classified into discrete habitat parcels using a habitat classification system appropriate to the project geography. The classification system should be one used by the region-appropriate biodiversity accounting metric (for example, the SGBA habitat typology for Singapore and the wider Southeast Asian ecoregion, or the UK Habitat Classification for Defra Metric applications for use in the UK), so that habitat types are recognised and per-hectare distinctiveness values can be assigned consistently. Classification is undertaken by a suitably qualified ecologist through a combination of desk-based review (satellite imagery, existing habitat mapping, ecological literature) and on-the-ground field survey. Each mapped parcel is drawn as a discrete polygon with recorded area (hectares), spatially referenced for re-survey at future monitoring rounds.
- Condition assessment. For each mapped parcel, a habitat-condition assessment is undertaken by a suitably qualified ecologist against the criteria specified by the region-appropriate biodiversity accounting metric. Condition criteria typically cover structural attributes (canopy cover, vegetation layering, tree size distribution, deadwood presence, understorey composition), compositional attributes (native species presence and cover, invasive species presence and cover, indicator species) and landscape context (connectivity to other habitat, buffer condition). The output is a condition category (typically Good, Moderate, Poor, or a numerical equivalent) for each parcel, together with the underlying field data supporting the categorisation. The condition assessment is recorded at the level of the parcel and held on file with the underlying evidence, so that the categorisation can be re-audited by a verifier.

Both activities are conducted at baseline and repeated at each subsequent monitoring round, with the parcel boundaries and classification held stable across rounds so that condition change is attributable to ecological recovery rather than to changes in the mapping. Where the survey team is extended to also collect tree-level measurements at the parcel level, as described in the enhanced tree-level field data collection passage above, those measurements form part of the same field visit rather than a separate exercise.

**Enhanced tree-level field data collection.** Where project resources allow, the biodiversity accounting field survey for forested and woodland habitats should be extended to capture tree-level measurements: species identification, individual tree size (diameter at breast height, DBH, measured at 1.3 m above ground level; and/or height where DBH is not practical), and stem density per unit area. These measurements are recorded within each condition-assessment plot alongside the standard habitat-condition variables required for the biodiversity accounting metric.

The additional data has two downstream uses:

- It strengthens the biodiversity accounting condition assessment by grounding structural condition scores in quantitative measurements rather than qualitative observation alone.
- More consequentially for the wider NCI, it provides the field input required for the detailed option for the carbon metric assessment method to derive parcel-specific per-hectare carbon stock values through allometric equations, in place of literature-average values applied to the habitat type as a whole.

## Metric 2: Soil Biota Community Composition

Soil biota are foundational to ecosystem function but are routinely overlooked in biodiversity assessments. The Composite Biodiversity Index captures them through eDNA metabarcoding analysis of bacterial and fungal communities, taxa that together drive nutrient cycling, decomposition, plant productivity, and soil structure.

Soil samples are taken across each habitat parcel, sent to a laboratory, and processed to amplify DNA fragments from two target taxonomic groups: bacteria and fungi. Where possible, samples are taken from each distinct habitat type, including those with differing condition scores. Sampling should follow habitat classification and completion of the habitat condition assessments used for the biodiversity accounting metric (Biodiversity Metric 1), ensuring the eDNA baseline is set against a fully characterised parcel.

Once samples are processed by an accredited lab through metabarcoding assays selecting for bacterial (16S rRNA) and fungal (ITS) regions, the relative abundance of each detected taxon is determined for every sample. These taxonomic profiles describe the soil microbial community composition of each habitat within the parcel.

**Comparison against reference and scoring.** The bacterial and fungal community profile of each parcel is compared against a paired reference site, the closest available approximation of an undisturbed natural state for the habitat being assessed. This is because soil community composition has no computable target value, only a degree of similarity to an observed healthy state.

Where pristine reference data is insufficient to confidently calibrate the eDNA dissimilarity score (for example, where reference data density for the broader ecoregion is sparse, or where no suitable on-site reference can be identified at the time of baselining), the eDNA metric may be reported as supporting data alongside the index rather than aggregated into the Composite Biodiversity Index, with the rationale documented and the position revisited at subsequent monitoring rounds as reference data improves. This provision applies at any tier; where it is invoked at Tier 2, the project is reporting on a two-metric Composite Biodiversity Index (Metric 1 plus Metric 3) for that round, with Metric 2 carried as supporting data, and may move to the full three-metric aggregation in later rounds once reference data permits.

The comparison uses Bray-Curtis dissimilarity calculated on Hellinger-transformed data, producing a single dissimilarity value bounded between 0 (compositionally identical to reference) and 1 (maximally divergent); research has shown that Hellinger-transformed data performs slightly better compared with distance of dissimilarity matrix (Laporte et a., 2021). This is converted to a normalised score by taking 1 − Bray-Curtis dissimilarity, where 1 represents full compositional parity with the reference and 0 represents maximum divergence. The score contributes directly to the parcel's Composite Biodiversity Index calculation.

**Visual representation and trajectory tracking.** The dissimilarity matrix is visualised through Non-metric Multidimensional Scaling (NMDS), an ordination method that reduces the complexity of eDNA data into a two-dimensional plot, where samples with similar community composition appear close together and dissimilar samples appear far apart. As habitats mature under management, their eDNA community profiles should track towards the reference site cluster in ordination space, providing a visual line of evidence on ecosystem trajectory that complements the scalar score. Stress values are reported with every ordination, with configurations exceeding 0.2 flagged for caution following Clarke (1993).

**Interpretation of change over time.** Where multiple sampling rounds or multiple parcels within a habitat type are compared, apparent differences in community composition are tested for statistical significance using PERMANOVA (Permutational Multivariate Analysis of Variance)[2]. This confirms whether observed differences — for example, movement of a parcel closer to reference between baseline and revisit — reflect a genuine compositional shift rather than sampling variability. PERMDISP is run alongside to distinguish between-group differences from within-group dispersion. These tests support interpretation of trajectory but do not enter the metric calculation directly.

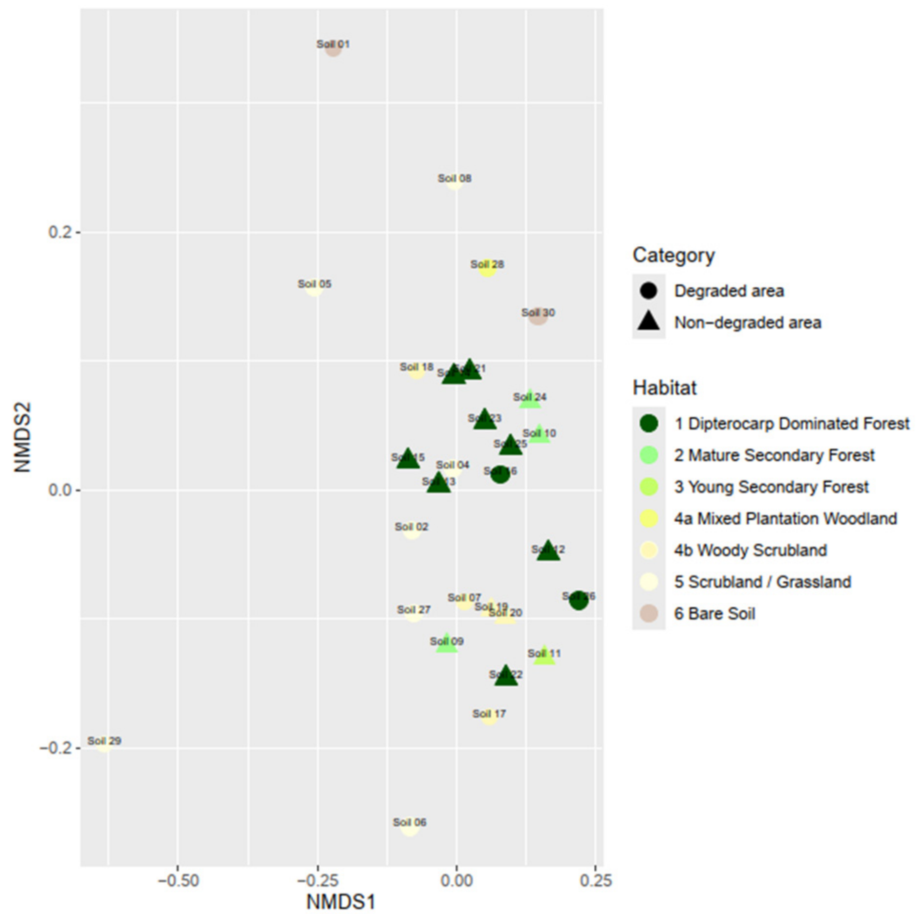



Figure 8. Non-metric multidimensional scaling (NMDS) ordination of soil biota communities across habitat types and degradation categories at the Bintan Island Pilot Site. Point shape denotes degradation category (circles: degraded; triangles: non-degraded); colour denotes habitat type across a gradient from early successional (Bare Soil, Scrubland/Grassland) to mature forest (Dipterocarp Dominated Forest). Closer proximity in ordination space indicates greater community similarity.

[2]PERMANOVA (Permutational Multivariate Analysis of Variance) is used to test whether the differences between groups are statistically meaningful or could plausibly have arisen by chance. The test works by comparing the observed grouping against 999 randomly reshuffled versions of the same data — if the real grouping produces stronger separation than the reshuffled versions, the pattern is unlikely to be coincidental. PERMDISP is run alongside to confirm that any detected difference reflects a genuine shift in community composition rather than one group simply being more variable than another.

## Metric 3: Fauna Species Diversity

Above-ground faunal diversity is represented through passive acoustic monitoring (PAM) data. The metric primarily captures birds, bats, amphibians, and stridulating insects.

The rationale for using soundscape data as a proxy for fauna species diversity rests on the acoustic niche hypothesis (Krause 1993), which holds that co-occurring vocalising species partition acoustic space (by frequency, by time of day, by temporal pattern) to avoid signal masking. As species accumulate in a recovering ecosystem, more frequency bands are occupied, vocalisation activity becomes more sustained across the diel cycle, and the soundscape becomes measurably more complex. Soundscape ecology (Pijanowski et al. 2011) formalises this by distinguishing three sources of sound in any landscape: biophony (biological sound, e.g. bird calls and insect stridulation), anthrophony (human-generated sound, e.g. traffic and machinery), and geophony (non-biological natural sound, e.g. wind and rain). Biophony is the signal of interest for the metric; the sampling schedule and recording-selection rules described below isolate it from the other two. Acoustic indices including ACI, ADI, and the Bioacoustic Index have been validated against ground-truthed bird species richness across temperate, boreal, and tropical ecosystems (Boelman et al. 2007; Sueur et al. 2008; Pieretti et al. 2011), and tropical forest studies have demonstrated that soundscape complexity tracks habitat recovery trajectories over multi-year restoration timeframes (Burivalova et al. 2019).

The relationship is not a one-to-one mapping; indices respond to vocalisation activity rather than species identity, and acoustically dominant species can mask less vocal ones. But as a composite metric compared against a paired reference site, the signal is robust enough to detect both degradation and recovery at the parcel scale. Operationally, bioacoustic data is time-stamped, geolocated, and tamper-resistant, and can be re-analysed years later as classification models improve, properties that matter as much for assurance and verification as for the underlying ecological signal.

**Recorder configuration.** Each deployment uses a Wildlife Acoustics Song Meter Micro 2 (or equivalent device), a compact, IP67-rated passive acoustic recorder selected for its small footprint, low unit cost, and ability to scale across large landscapes. Configuration settings are held identical across all units in a project to ensure inter-site comparability:

- Sample rate — 48,000 Hz. Under the Nyquist–Shannon sampling theorem, a recorder resolves sound up to half its sample rate, so 48 kHz captures frequencies up to 24 kHz. This covers the full vocalisation range of all target taxa: birds (typically 1–8 kHz, some passerines to 12 kHz), amphibians (200 Hz – 5 kHz), and orthopteran insects (stridulation up to ~20 kHz). The Micro 2's onboard microphone has a flat response from 100 Hz to ~18 kHz, so 48 kHz matches the usable bandwidth without storing empty headroom. Higher sample rates are reserved for dedicated bat echolocation surveys, which require an extended ultrasonic microphone the Micro 2 is not optimised for.
- File format — 16-bit PCM WAV (mono). Lossless and supported by all major analysis platforms. WAV files are written with embedded GUANO metadata (recorder ID, GPS coordinates, timestamp, sample rate, gain), providing an auditable chain of custody for each recording.
- Gain — +18 dB (default). Reduced to +12 dB adjacent to roads, settlements, or other persistent anthropogenic noise to prevent clipping. Gain settings are logged in file metadata and held constant within a deployment.

**Recorder deployment.** Deployment density follows a spacing-and-buffering rule. Two distances govern placement: the minimum spacing between recorders, which keeps samples spatially independent, and the detection radius, which keeps each recorder's coverage within a single habitat-condition class.

1. **Minimum spacing between recorders.** Recorders are placed a minimum of 250 m apart, giving one recorder per 250 m by 250 m cell (approximately 6.25 hectares of effective coverage). This spacing keeps sampling locations spatially independent and prevents the same individuals being recorded by two units. The 250 m figure is a spacing rule, not a detection radius. It is a defensible default for dense tropical forest, where sound attenuates rapidly (Haupert et al. 2023). Projects in more open or acoustically transmissive habitats should widen the spacing accordingly, using a habitat-appropriate detection-distance calculation (the $a_0$ coefficient in Haupert et al. 2023 provides one such approach) and document the rationale.
2. **Number of recorders per parcel.** Each parcel receives a minimum of one recorder regardless of size. A second or further recorder is added only where the parcel is large enough to site it at least 250 m from the others i.e., for every additional 6.25ha. A compact 7-hectare parcel therefore receives one recorder, not two, because a second could not be independently spaced. For elongated parcels, the 250 m spacing rather than the area figure determines whether a second recorder fits; surrounding habitat parcels and respective recorder placements should also be taken into consideration
3. **Small or tightly fragmented parcels.** Where a parcel is too small, or too closely surrounded by distinct neighbours, for a recorder to represent a single habitat-condition class cleanly, it is not given a dedicated recorder. Instead, adjacent small parcels of differing condition are recorded together as a single acoustic mosaic, with one recorder placed in the largest or most representative patch and the mixed-class sampling reported as a known limitation for that location. This avoids deploying devices that cannot produce a clean, attributable sample.
4. **Siting and logging.** Within these constraints, each recorder should be positioned away from persistent artificial noise sources (roads, settlements, machinery) where possible, and mounted at 1.5–2 m on a tree trunk or stake. GPS coordinates, mounting height, habitat-condition class, distance to nearest distinct-class boundary, and deployment start/end times are logged for every unit.

**Recording frequency.** It is recommended that each recorder should operate on a minimum 5-day schedule (where possible, aim for more, but ensure the frequency is applied consistently through baseline to monitoring phase), capturing 1-minute audio samples every 3 minutes (total of 20, one-minute recordings per hour) across three diel (24-hour) windows when vocalising fauna are most active: dawn chorus (1 hour either side of sunrise), dusk chorus (1 hour either side of sunset), and nocturnal (23:00–03:00 local) (Shaw et al, 2022). Audio is recorded in WAV format at 48 kHz, 16-bit, to capture the full frequency range of the local soniferous fauna.

Other schedules can be considered, providing they are backed up by research for any particular ecosystem or ecoregion. The agreed schedule and frequency must be consistently applied for a given project. Where distinct breeding seasons occur (i.e., in temperate locations), devices should ideally be deployed during said season for both baselining and monitoring.

**Audio pre-processing.** Files are screened to remove segments dominated by rain, wind, or anthropogenic noise, combining automated quality-control filters with manual review of a stratified subsample to validate filter performance. The retained audio forms the analytical dataset for index computation.

**Acoustic indices.** The cleaned audio is batch processed through a suite of established acoustic indices using software such as Kaleidoscope Pro (Wildlife Acoustics, Inc.). Six indices are computed for each recording:

- Normalised Difference Soundscape Index (NDSI)
- Acoustic Complexity Index (ACI)
- Acoustic Diversity Index (ADI)
- Acoustic Evenness Index (AEI)
- Shannon Entropy (SH)
- Bioacoustic Index (BI)

Each index captures a different dimension of the soundscape (frequency distribution, temporal complexity, evenness across frequency bands, and overall biological signal), so the combined output reflects multiple complementary signatures of faunal activity rather than any single acoustic property. This follows contemporary methods in bioacoustic proxy analysis (e.g. Allen-Ankins *et al.* 2023). The purpose of averaging the outputs of six different indices is due to the way the different indices behave, with each capturing different dimensions of a soundscape, and each being different to specific conditions (e.g., some more affected by rain, wind, saturation or loud species), a composite provides greater coverage across species occupying different acoustic niches.

**Bioacoustic Composite Metric (BCM) construction.** The six acoustic indices are reported on very different scales: the Acoustic Complexity Index may run into the thousands while the Normalised Difference Soundscape Index ranges from −1 to +1, so they cannot be combined directly. They are brought onto a common footing in two distinct steps, applied in order.

First, standardisation. Each index is converted to a z-score across the project dataset:

$$z = (\text{value} - \text{mean}) / \text{standard deviation}$$

This centres each index on zero and scales it by its own spread, so that an index with a large numeric range no longer dominates one with a small range. (Omitting this step, by scaling the raw values directly, is a common error that lets wide-ranging indices swamp the composite.)

Second, min-max scaling. Each standardised index is rescaled to a 0–1 range:

$$\text{scaled} = (z - \text{min}) / (\text{max} - \text{min})$$

The six scaled indices are then combined by equal-weighted average to produce the Bioacoustic Composite Metric (BCM) for each recording. Equal weighting is consistent with the equal-weighting principle applied throughout the NCi and makes no prior claim that one acoustic index matters more than another. The BCM is calculated per diel window (dawn, dusk, nocturnal) and averaged across windows to give a single parcel-level value.

One directional check is applied before averaging. Each of the six acoustic indices must point the same way, with higher values indicating greater acoustic diversity or activity. Five of the six indices, ACI, ADI, BI, SH and NDSI, increase as vocalising activity and frequency-band occupancy increase, and so contribute to the BCM in their as-calculated direction. The Acoustic Evenness Index (AEI) is constructed differently: it is a Gini-coefficient-style measure of frequency-band dominance, which by construction increases as the soundscape becomes more dominated by a small number of frequency bands and decreases as occupancy is spread more evenly across the spectrum. AEI therefore points in the opposite direction from the other five indices, and a higher raw AEI corresponds to a less, not more, biologically rich soundscape. To bring it into the same direction as the others, AEI is always inverted before entering the BCM , by taking 1 minus its scaled value. With this inversion applied, all six indices contribute in the same direction and the equal-weighted average is meaningful. Without it, AEI would subtract signal from the BCM while the other five indices added it, biasing the composite.

**Comparison against reference and scoring.** Each parcel's BCM is compared against the BCM of the paired reference site, recorded under matched conditions (same season, same diel windows, equivalent recorder model and sample rate). The metric score is the parcel BCM expressed relative to the reference BCM, bounded between 0 and 1, where 1 represents soundscape complexity equivalent to or exceeding the climax reference and 0 represents acoustic silence. This places the bioacoustic metric in the reference-state-similarity normalisation mode: it is benchmarked against the climax reference rather than an interim successional target, because a soundscape has no computable target value, only a degree of similarity to an observed healthy state.

**Caveats on interpretation.** Acoustic indices are proxies for biodiversity rather than direct counts of species: they capture soundscape activity and complexity, which correlate with but are not identical to the number of vocalising species present. To strengthen the metric, audio is additionally processed to generate verified species detections, which feed into the conservation-significant species layer in the supporting evidence section. The BCM and the species-detection output are reported alongside each other so that index trends can be interpreted against actual community changes.

## Supporting Evidence: Beyond the Index

The three metrics form the spine of the Composite Biodiversity Index. Around them sits a supporting evidence layer that does not enter the index calculation directly but enriches the ecological narrative and is essential for site management. This layer includes:

- **Walkover surveys** — used to ground-truth habitat mapping derived from satellite imagery, and to record vegetation composition at parcel level.
- **Camera trap data** — deployed to collect supplementary data on fauna. Camera traps provide evidence only and are not used as an index input: they generate presence-absence data that complements the bioacoustic and eDNA signals, particularly for medium-to-large mammals.
- **IUCN Red List species** — compiled across all survey methods (eDNA, camera traps, bioacoustics, walkover) and reported separately. This protects the salience of high-value species that would otherwise be diluted in a quantitative index. Where possible, additional data such as aquatic eDNA samples should be taken to identify further fauna species presence within a site.

## Aggregation Logic

In the full NCi methodology, the three biodiversity metrics are combined through equal weighting, each contributes one-third to the final Composite Biodiversity Index. Equal weighting is intentional: it makes no prior claim that one dimension of biodiversity matters more than another, and it is straightforward to justify to verifiers.

Equal weighting is the current default. Future iterations may introduce weighted schemes where the ecological evidence supports differentiation. For example, where guild and functional trait diversity metrics are integrated as additional or replacement composition measures. Any change to the weighting will be documented and version-controlled, with prior project data remaining traceable to the methodology version under which it was generated.

# Chapter 4

## Ecosystem Service Metrics Component

Where the Composite Biodiversity Index captures composition and structure, the ecosystem service component captures function. It measures what the ecosystem actually does i.e., how much carbon it stores, how much pollution it removes, how much it slows runoff, how well it builds soil. Four metrics are tracked, each through an established analytical method with literature-supported inputs. Each is reported in its absolute physical units (the individual ecosystem service performance layer) and is also expressed as a progress-to-target score on the 0–1 scale for the Composite NCi Score, as set out in the Reference Site and Normalisation section.

### The Soil Index: Soil Quality

Soil organic matter (SOM) is used as the headline soil quality indicator. SOM correlates strongly with multiple downstream functions, nutrient cycling, water retention, microbial diversity, erosion resistance, and is measurable at relatively low cost.

**Sampling design and analysis.** A sampling design must be documented before fieldwork begins and held constant from baseline through every subsequent monitoring round, so that change over time is attributable to ecological recovery rather than to changes in the sampling protocol.

The design must specify the number of samples per habitat type per parcel, the sampling locations (recorded by GPS for re-occupation at monitoring), and the depth profile from which samples are taken. Replication should be sufficient to characterise within-habitat variability and capture spike values where they occur; a minimum of one sample per habitat type per parcel is the lower bound, with additional samples in larger or more heterogeneous parcels.

Where field samples are unavailable for a particular habitat type at the project location, or are present in such limited number that they cannot reliably characterise the habitat, region-specific literature values may be substituted, with the source documented and the use of literature flagged in reporting.

Samples are analysed for soil organic matter (SOM) by an accredited laboratory using an established analytical method; the Walkley and Black (1934) wet oxidation method is the principal reference for SOM determination and remains widely used internationally, with current standardised procedure described in FAO/ITPS (2019). Other established SOM methods (for example, loss-on-ignition or dry combustion) may be substituted where consistent with the project context, provided that the method is fixed at baseline and not changed across monitoring cycles, and that the analytical standard is documented for verification.

Per-habitat SOM averages are calculated and applied across each parcel. The site-level baseline value is the area-weighted mean across all parcels. Projection values are derived by applying the expected post-restoration habitat SOM averages, supported where necessary by region-specific literature on soil recovery trajectories.

**Use of literature values at Tier 1.** At Tier 1, where the project is reporting in absolute units and the normalised Composite NCi Score is not yet being produced, the SOM baseline may be derived from region-specific, habitat-matched literature values rather than from field samples, provided the source is documented, the values used are locked at the point of baselining, and the use of literature is flagged in reporting. This provision gives Tier 1 projects a workable on-ramp without committing to the full field programme at the outset, and is consistent with the tier's purpose of supporting early-stage decisions and absolute-unit performance tracking. A literature-derived baseline is, however, materially less robust than a field-sampled one, and projects are expected to advance to field-sampled SOM data as the project develops.

**Transition from a literature baseline (Tier 1) to a field-sampled baseline (Tier 2).** Where a project starts at Tier 1 with a literature SOM baseline and later commissions field SOM sampling, the treatment of the field data depends on the timing of the samples relative to restoration interventions on the parcel. If field samples are collected before any intervention has begun on a parcel, those samples replace the literature value as the parcel's baseline of record. If field samples are collected after interventions have begun, they cannot be retrofitted into a pre-intervention baseline; the literature value remains the baseline of record for that parcel, and the field samples enter the project's data as the first field-measured monitoring round, against which subsequent monitoring is tracked. This rule applies independently of which tier the project is on at the time of sampling; a Tier 2 upgrade does not, by itself, create the right to re-baseline a parcel where interventions have already begun.

The principle is consistent with the wider baseline-integrity rule set out in the NCI Architecture section: the only baseline that can be measured with full integrity is the one captured before works start.

**Normalisation.** The soil metric is scored as current SOM divided by the parcel's projected-target SOM (progress-to-target), with the absolute SOM percentage retained as the reported value.

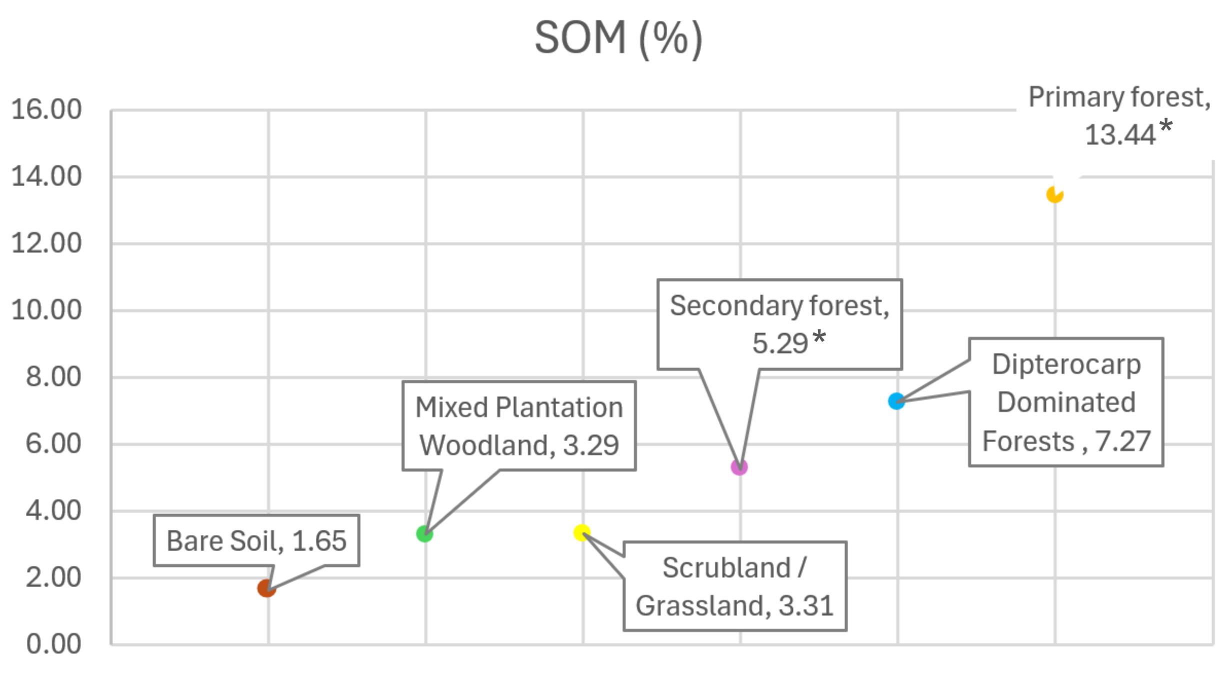



Figure 9. Soil organic matter (SOM, %) across the habitat gradient at the Bintan pilot, rising from bare soil (1.65%) through mixed plantation woodland (3.29%), scrubland/grassland (3.31%), secondary forest (5.29%) and dipterocarp-dominated forest (7.27%) to primary forest (13.44%). Values inform the parcel-level soil metric baseline and its progress-to-target normalisation.

## The Water Index: Water Regulation

The water metric captures two ecosystem-service outcomes simultaneously: the regulation of surface runoff, and the reduction of total suspended solids (TSS) carried into receiving water bodies. Both outcomes are driven by the same underlying mechanism, the conversion of degraded land to vegetated cover that intercepts rainfall, increases infiltration and reduces erosive surface flow, and the two are combined into a single Water Index for the parcel and the site.

**Modelling framework.** The metric is built on a continuous hydrological model that translates the parcel's land cover into volumetric runoff and TSS load under realistic rainfall conditions. Any continuous rainfall-runoff and water-quality model that accepts spatially distributed land cover, soils and meteorological inputs and produces volumetric runoff and TSS load outputs at sub-catchment scale may be used, provided the choice is documented and held constant across baseline and monitoring rounds.

As an example, the Bintan Pilot used the U.S. Environmental Protection Agency Storm Water Management Model (EPA SWMM 5.2; Rossman, 2015), a well-established, peer-reviewed and openly documented rainfall-runoff and water-quality model originally developed for stormwater management but widely applied in catchment-scale ecosystem-service assessments.

**Spatial framework.** The model area is delineated into sub-catchments derived from a digital elevation model (DEM), using GIS to compute flow direction, accumulation and watershed boundaries. Each sub-catchment is parameterised separately for area, slope, soil type, vegetation cover and infiltration characteristics, so that local hydrological response is preserved rather than averaged across the project area.

As an example, for the Bintan Pilot, the DEM was sourced from the Alaska Satellite Facility (ASF), watershed delineation was performed in ArcGIS Pro, and the 100-hectare project area resolved into 11 sub-catchments grouped across three regional clusters (North, West, South).

**Inputs and data sources.** The model requires five categories of input. Each is briefly described below, with the data and software used for the Bintan Pilot provided as an example:

1. Topography: a DEM sufficient to delineate sub-catchments at the scale of the project area. Bintan used ASF DEM data (https://search.asf.alaska.edu).
2. Rainfall: a multi-year precipitation time series of sufficient length to capture annual and seasonal variability. Bintan used average annual and monthly precipitation data from 1991 to 2020 supplied by the local meteorological office.
3. Land use and habitat: the baseline habitat map (the same map used for the biodiversity accounting metric) and the projected post-restoration habitat map.
4. Soils: soil type and the corresponding maximum and minimum infiltration rates for each soil-habitat combination. Bintan used local soil mapping cross-referenced against the SWMM default parameter ranges documented in the EPA SWMM 5.2 user manual.
5. Evapotranspiration: average monthly potential evapotranspiration data of sufficient length to capture seasonal variability. Bintan used average monthly PET from 1981 to 2020 derived from Santoso and Marganingrum (2022), a Bintan-specific climate study.

**Scenario structure.** The model is run twice: once in relation to the baseline habitats (current condition), and once on the projected post-restoration habitats. The two runs use identical rainfall, soil and evapotranspiration inputs; the only difference between them is land cover. This isolates the hydrological effect of restoration from inter-annual climate variability and ensures that the projected uplift is attributable to ecological recovery rather than to differences in weather between modelling years.

**Outputs.** For each scenario and each sub-catchment, the model produces volumetric outputs for total precipitation, evaporation, infiltration and surface runoff, alongside TSS washoff loads. From these, two ecosystem-service indicators are extracted at the project boundary: total annual surface runoff ($m^3$/year) and total annual TSS washoff (kg/year). A diagnostic Captured Runoff Ratio (Total Infiltration ÷ Total Precipitation) may additionally be reported as a transparent indicator of how much rainfall the parcel is now retaining on site rather than shedding downstream.

**Composite Index construction.** Runoff and TSS outputs are reported on different scales ($m^3$/year for runoff, kg/year for TSS) and cannot be combined directly. Each is therefore first standardised to a 0–1 scale by min-max normalisation, applied across the baseline and projected scenarios for the parcel.

**Normalisation into the NCi.** The Water Index produced by the modelling step is itself already on a standardised scale, but it does not yet express progress against a parcel-specific target. For inclusion in the NCi Score, the Water Index is expressed as progress toward the parcel's projected-target Water Composite Index value (current ÷ projected target), consistent with the progress-to-target normalisation applied to the four ecosystem-service metrics across the methodology. The underlying standardised Water Index value is retained as the reported value alongside the normalised score, so that the absolute hydrological outcome is preserved.

**Caveats and known site-calibration vulnerabilities.** Three vulnerabilities should be disclosed by any project using this metric:

1. SWMM was originally developed for engineered stormwater systems, and its default parameters reflect that context; applying it to a natural restoration site requires that soil and vegetation parameters be selected appropriately and held constant across baseline and monitoring rounds.
2. The projected-scenario habitat map is itself a forecast, and the hydrological projection inherits any uncertainty in that forecast; the projected Water Index is therefore an indicative target value, refined as actual habitat condition is monitored.
3. The rainfall and PET inputs are climatological averages, and the model does not, in its baseline configuration, simulate extreme event response; projects requiring extreme-event analysis should run additional scenarios documented separately from the baseline metric.

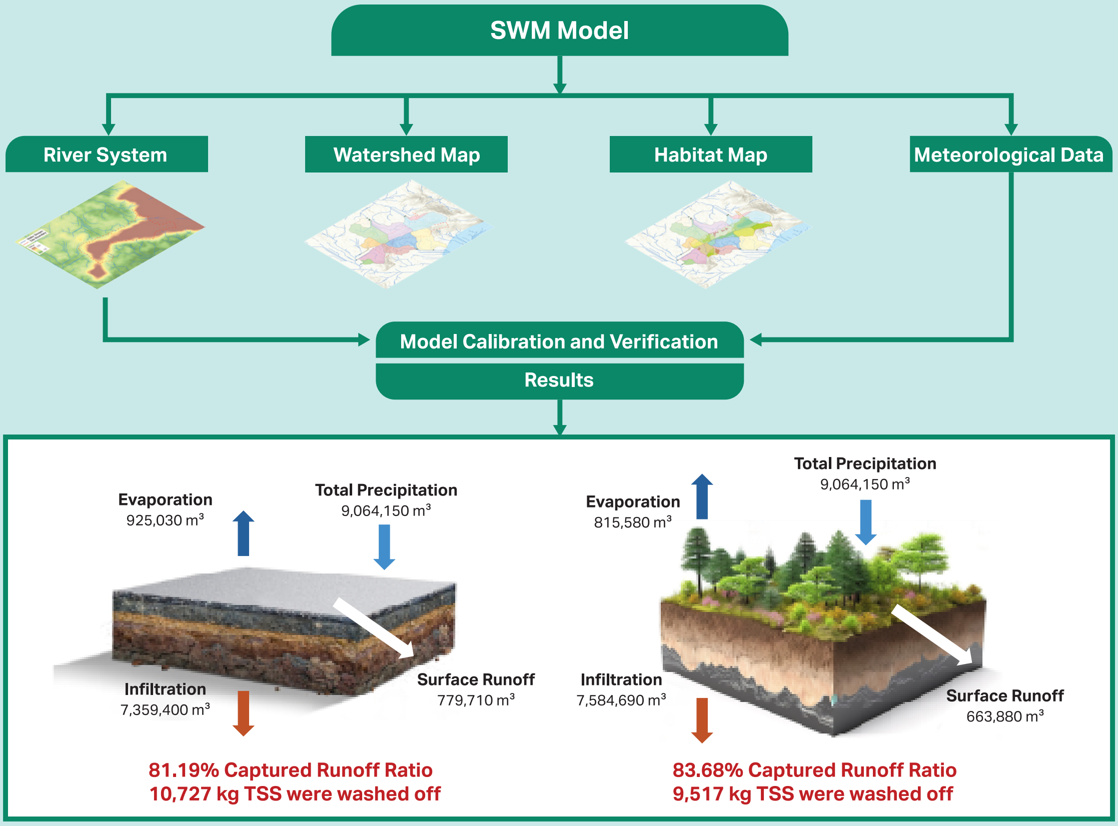



Figure 10. Storm Water Management Model workflow and modelled water-balance outputs for the Bintan pilot. Model inputs (river system, watershed delineation, habitat map, and meteorological data) feed model calibration and verification. Results compare the baseline (degraded) and projected post-restoration land-cover scenarios under identical rainfall, soils and evapotranspiration inputs.

## The Air Index: Air Quality

Vegetation removes airborne fine particulate matter ($PM_{2.5}$) through dry deposition: particles are intercepted by leaf and branch surfaces, where they are retained until rainfall, leaf fall or wind-driven resuspension returns them to the atmosphere. The net removal achieved by a parcel of vegetation depends on the density of leaf surface available for interception, the ambient particulate concentration the canopy is exposed to, the effective deposition velocity at which particles settle, the fraction subsequently lost to resuspension, and the number of days each year during which the canopy is dry and therefore active as a sink.

**Modelling framework.** The metric is built on the dry deposition formulation of Xiao et al. (2015), which expresses annual $PM_{2.5}$ reduction by a vegetated parcel as the product of these factors:

$$q\_pi = D \times V\_d \times C\_p \times 3600 \times LAI\_i \times 24 \times (1 - R) / 1{,}000{,}000$$

Where q_pi is annual $PM_{2.5}$ reduction (tonnes per hectare per year), D is the number of no-rain days per year, V_d is the $PM_{2.5}$ deposition velocity (m/s), C_p is ambient $PM_{2.5}$ concentration ($g/m^3$), LAI_i is the leaf area index of the i-th pixel or habitat patch ($m^2$ leaf area per $m^2$ ground area), R is the resuspension fraction, and the numerical constants convert from hourly seconds and per-million-grams to annual tonnes. The formulation is widely used in vegetation-based $PM_{2.5}$ removal accounting and is computationally tractable from spatial inputs that most projects can resource.

**Inputs and data sources.** The model is driven by five parameter inputs. Each is described below, with the Bintan example given to illustrate one defensible implementation:

1. Number of no-rain days per year (D): a multi-year climatology of dry days at the project location, since wet days reset the canopy and remove retained particulates. Bintan used D = 196 days, derived from Weather Spark climatology for Bandar Seri Bentan.
2. Deposition velocity (V_d) and resuspension fraction (R): both vary with wind speed; the canonical source for these parameters by wind-speed bin is Nowak et al. (2013), Table 3, derived from modelled $PM_{2.5}$ removal by trees in ten U.S. cities. Bintan used the mean annual wind speed of 4.0 m/s, which gives V_d = 0.0017 m/s (0.17 cm/s) and R = 0.06 from Nowak et al. (2013). Projects with stronger wind-speed records may improve calibration by binning the calculation across the local wind-speed distribution rather than applying a single annual mean.
3. Ambient $PM_{2.5}$ concentration (C_p): the local ambient $PM_{2.5}$ concentration to which the canopy is exposed, ideally a multi-year mean from a project-relevant air-quality monitoring station. Where direct $PM_{2.5}$ measurements are not available, the ambient $PM_{2.5}$ concentration may be derived from local Air Quality Index (AQI) records via the U.S. EPA AirNow AQI Calculator or an equivalent recognised conversion tool. Bintan used C_p = 2.14 $\times 10^{-5}$ g/m³ (21.4 μg/m³), derived from the 2023 wet-season AQI of 74 via the AirNow AQI Calculator.
4. Leaf Area Index (LAI): the leaf surface area per unit ground area for each habitat type within the project area. LAI is the principal driver of removal capacity in the formulation: doubling LAI doubles annual removal, all other parameters held constant. LAI may be derived from one of two routes, depending on the data available to the project:
   - Habitat-type LAI values drawn from published region-appropriate ecological studies, applied to the habitat map at parcel level; or
   - NDVI-derived LAI, in which the Normalised Difference Vegetation Index is calculated from satellite imagery for each pixel and converted to LAI via a published NDVI-to-LAI regression. The Bintan implementation used both routes and cross-checked one against the other: NDVI was derived from Landsat 8 imagery (30 m × 30 m pixel resolution) in ArcGIS Pro, and converted to LAI using the regressions of Xiao et al. (2015) (LAI = 9.7471 × NDVI + 0.3718 for forest; LAI = 3.227 × NDVI / NDVI_avg for grassland). The resulting LAI values were cross-checked against a published Indonesian tropical-forest LAI study (132 plots, lowland forest), which reported empirical LAI ranges of 4.2–7.3 (mean 5.9) for forest and 1.8–6.6 (mean 4.3) for shrubland.

**Outputs.** The model produces, for each habitat type within the project area, an annual $PM_{2.5}$ removal rate in tonnes per hectare per year. These per-habitat rates are then multiplied by the habitat-extent area in the baseline and projected habitat maps respectively, and summed to give the total annual $PM_{2.5}$ removal (tonnes per year) at site level under each scenario.

As an example, for the Bintan Pilot, the forest annual removal rate worked out at 0.024–0.049 tonnes/ha/year (mean 0.037) and shrubland/grassland at 0.010–0.025 tonnes/ha/year (mean 0.018).

**Normalisation into the NCi.** The air metric is expressed as progress toward the parcel's projected-target removal value (current removal ÷ projected target removal), consistent with the progress-to-target normalisation applied to the four ecosystem-service metrics across the methodology. The underlying absolute removal value (tonnes per year) is retained as the reported value alongside the normalised score, so that the physical outcome remains inspectable.

**Caveats and known site-calibration vulnerabilities.** Four vulnerabilities should be disclosed by any project using this metric:

1. The Xiao et al. (2015) formulation was developed and parameterised for urban green space in Beijing. Applying it to tropical forest involves an extrapolation from the conditions under which the model was calibrated, and project teams should consider whether the underlying assumptions (notably the linear scaling of removal with LAI) hold for their site. Cross-validation against a habitat-type-appropriate empirical LAI source, as done at Bintan, is recommended.
2. The V_d and R parameters from Nowak et al. (2013) are wind-speed-dependent, and applying a single annual-mean wind speed smooths over real temporal variation in dry deposition. Projects with multi-year hourly wind records may strengthen the calculation by binning V_d and R across the local wind-speed distribution rather than applying single annual-mean values.
3. The NDVI-to-LAI conversion LAI = 9.7471 × NDVI + 0.3718 was developed for Beijing urban green space. When applied to high-NDVI tropical forest (NDVI ≈ 0.84 at Bintan), it yields LAI ≈ 8.56, which sits above the empirical maximum (7.3) observed in the Indonesian forest study used as the cross-check reference. The Bintan implementation retained the Xiao regression rather than re-fitting locally, and disclosed the resulting LAI as a high-end estimate. Projects in non-temperate forest contexts are encouraged to consider whether a locally-fitted NDVI-to-LAI conversion would improve site calibration.
4. The metric captures dry-deposition $PM_{2.5}$ removal only. Other air-quality services (deposition of larger particulates, deposition of gaseous pollutants such as NO_x and $O_3$, biogenic VOC emissions that can act as a counter-service) are outside the scope of this metric in its current form. Where these services are material to the project geography, supplementary modelling should be considered alongside, rather than within, the air metric.

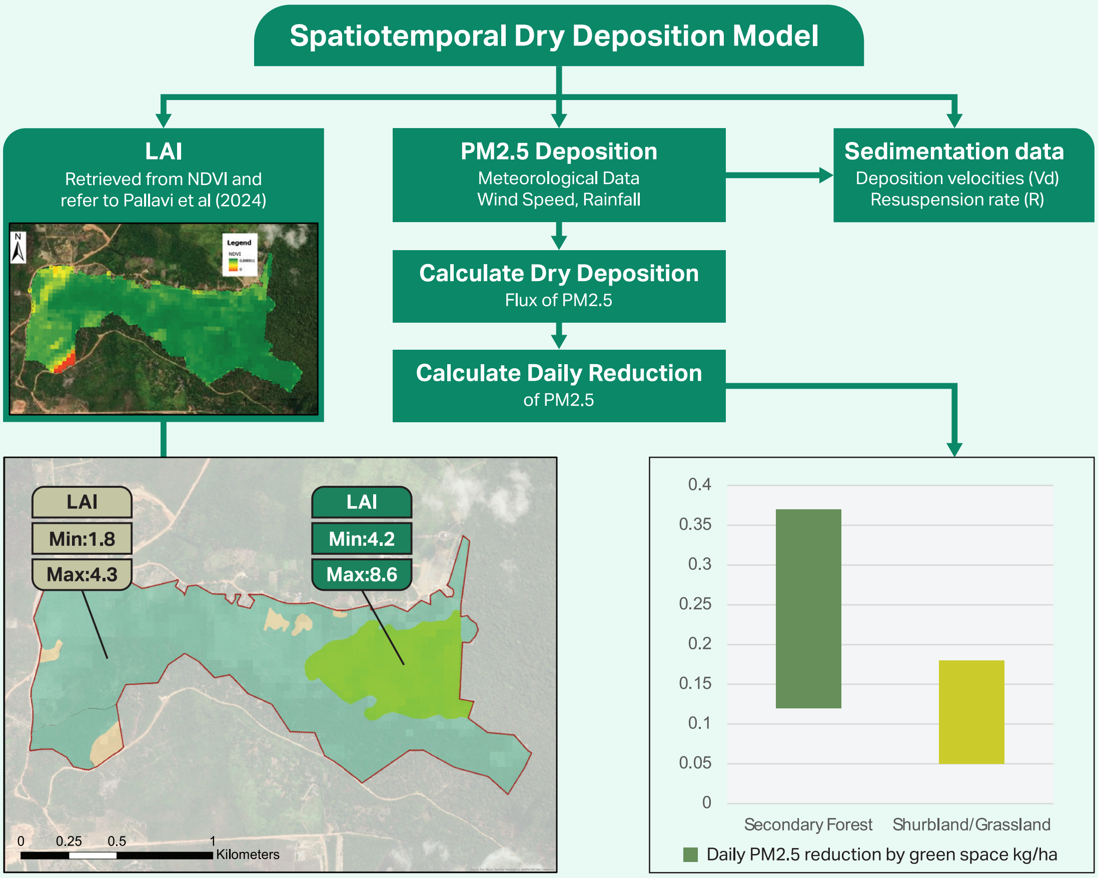



Figure 11. Spatiotemporal dry-deposition model workflow for the Bintan air-quality metric. Leaf area index (LAI), PM2.5 deposition parameters (meteorological data, wind speed, rainfall) and sedimentation parameters (deposition velocity Vd, resuspension fraction R) drive a dry-deposition flux calculation and a daily PM2.5 reduction estimate.

## Carbon Stock

Carbon is the most familiar of the four ecosystem-service indicators and is supported by a mature body of peer-reviewed scientific literature, an active suite of international standards (IPCC inventory guidance, REDD+ submissions, voluntary carbon market methodologies), and well-established field measurement techniques. The NCi does not introduce a new method for carbon accounting; instead, it draws on established literature-derived per-hectare carbon stocks for each habitat type at the project location, combined with parcel-level habitat extent data to produce total stock figures comparable with carbon market accounting conventions.

Alternatively, if the project allows, carbon stocks can be estimated based on individual tree data.

**Five-pool framework.** The NCi estimates carbon stocks across the five pools recognised in IPCC inventory guidance (IPCC, 2019): above-ground biomass (AGB), below-ground biomass (BGB), soil organic carbon, dead wood (woody debris), and litter. Each pool is measured separately, so that habitat types with materially different distributions across pools (for example, secondary forest with substantial AGB and BGB versus scrubland with dominant soil and AGB contributions only) are represented correctly rather than collapsed into a single per-hectare value. For habitats where a pool is empirically small (litter on bare soil) or where region-appropriate literature does not separately resolve a pool, the methodology may aggregate or omit pools provided the choice is documented and held constant across baseline and monitoring rounds.

**Per-hectare stock values.** For each habitat type at the project location, the carbon stock per pool (in tonnes of carbon per hectare, tC/ha) is drawn from peer-reviewed sources appropriate to the project geography. Using the Bintan Pilot example, the principal references for tropical Southeast Asian sites used included:

- FAO Forestry Paper proceedings (Lasco & Pulhin, 2004) for AGB and soil carbon in tropical Southeast Asian forest ecosystems.
- FAO grassland soil carbon assessment (Dondini et al., 2023) for soil organic carbon in non-forest tropical habitats.
- Indonesia National Forest Reference Level submission (Republic of Indonesia, 2022), the official UNFCCC REDD+ submission, for Indonesia-specific forest biomass parameters.
- Krisnawati et al. (2014) for the Indonesian National Carbon Accounting System (INCAS) emission factors derived from Central Kalimantan forest inventory data.
- IPCC 2019 Refinement (IPCC, 2019) where region-specific values are unavailable and Tier 1 default factors are appropriate.

The Bintan Pilot utilised these sources as follows:

- Secondary forest (the project's dipterocarp-dominated reference habitat) was parameterised at 67.5–125 tC/ha AGB (FAO), with a 102.1 tC/ha cross-check from the Indonesia REDD+ FRL submission and 106.2 tC/ha from Krisnawati et al.; 29.6–31.7 tC/ha BGB (REDD+ FRL and Krisnawati); 60 tC/ha soil organic carbon (FAO grassland soil carbon, applied as the regionally appropriate value); 33.15 tC/ha woody debris; and 3.7 tC/ha litter.
- Scrubland and grassland habitats were parameterised at 15–64.2 tC/ha AGB and 30 tC/ha soil organic carbon, again drawn from the same sources.
- Bare soil was treated more simply, with a single 67.5 tC/ha total reflecting limited above-ground biomass and minimal active pools.
- Total per-hectare ranges at Bintan were 194–254 tC/ha for secondary forest (mean 224 tC/ha) and 112–163 tC/ha for scrubland/grassland (mean 137 tC/ha).

**Calculation.** Total carbon stock per habitat type at parcel level is calculated as:

***Carbon Stock (tC) = Average carbon stock per hectare (tC/ha) × Habitat extent (ha)***

For each habitat type at the project location, the per-hectare value (summed across the five pools) is multiplied by the area of that habitat within the parcel. Habitat-level results are summed across the parcel to give the total carbon stock under each scenario, and across all parcels to give the project-level total. The same calculation is performed under the baseline habitat map and under the projected post-restoration habitat map; the difference is the projected carbon stock uplift.

**Deriving the per-hectare carbon stock for each parcel.** The per-hectare carbon stock value applied to each parcel is not a single fixed value drawn from literature. It is set through one of three routes, applied in order of preference according to the field data available for the parcel:

- **Route 1 — Direct calculation from field measurements:** where the biodiversity accounting field survey has recorded tree species composition, individual tree size (DBH and/or height) and stem density at the parcel level (see the enhanced tree-level field data collection passage under Metric 1), and where allometric equations appropriate to the dominant species and region are available, the tree-by-tree measurements are applied directly to those equations to produce a parcel-specific above-ground and below-ground biomass estimate. This estimate replaces the literature range value for the AGB and BGB pools.
- **Route 2 — Literature values adjusted by field condition:** where tree-level measurements are not available, but the biodiversity accounting field survey has captured qualitative habitat-condition data, the per-hectare literature range for the habitat type is used, adjusted to reflect the observed condition. A secondary forest parcel with high stem density and large mean DBH is set toward the upper end of the literature AGB and BGB ranges; a lower-condition parcel with lower density and smaller mean DBH is set toward the lower end. Route 2 is the standard application for the majority of parcels.
- **Route 3 — Literature values applied without field adjustment:** where field survey data is unavailable, the literature range mean for the habitat type is applied without adjustment. Route 3 is the fallback where field data cannot be collected, and its use should be documented at parcel level.

Across all three routes, the same field dataset is updated at each monitoring round, so that the per-hectare value applied to the parcel evolves as the parcel's actual condition develops. The route applied to each parcel should be documented and held constant across monitoring rounds where possible; a project advancing from route 3 to route 2, or from route 2 to route 1, should record the change and note the point at which the routing was upgraded, so that the change in carbon stock across the transition is transparent to the reader.

**Reporting and finance market interoperability.** Carbon stocks are reported in tonnes of carbon (tC) as the principal output of the metric. For finance market interoperability, tC values are also expressed as $CO_2$-equivalent ($tCO_2e$) using the stoichiometric conversion of 44/12 (i.e., 1 tC = 3.667 $tCO_2e$). Both units should be reported alongside one another in project disclosures, so that comparisons against carbon market accounting conventions (which typically report in $tCO_2e$) and against ecological literature (which typically reports in tC) are both possible without recalculation.

**Normalisation into the NCi.** The carbon metric is scored as current carbon stock divided by the parcel's projected-target carbon stock (progress-to-target), consistent with the four ecosystem-service metrics across the methodology. Where literature values give a habitat type a carbon density at or near its successional target at baseline (for example, a parcel that already supports near-mature forest), the parcel will score close to 1 for carbon with little projected uplift, correctly reflecting that for that parcel, recovery gains are concentrated in other metrics rather than in carbon. The absolute tonnage (tC and $tCO_2e$) is retained as the reported value alongside the normalised score.

**Caveats and known site-calibration vulnerabilities.** Two vulnerabilities should be disclosed by any project using this metric:

- The per-hectare carbon stock values are literature-derived and inherit the uncertainty of their source studies. Bintan's secondary forest AGB, for example, has a literature range of 67.5–125 tC/ha across three independent sources, a near-twofold spread. Projects should report the range as well as the central value, and the choice between using a literature range mean versus a more conservative lower bound versus a project-specific best estimate should be documented and held constant across monitoring rounds.
- The metric captures stock, not flux. Annual carbon sequestration rates (the rate at which the stock is growing) are not directly reported and would require either repeated stock measurements over multi-year intervals or supplementary flux-tower / growth-curve modelling. Projects intending to monetise the metric through carbon markets that price sequestration rate rather than stock should structure their reporting accordingly.

| Baseline Habitat Types[1] | Area (ha) | Baseline Average Carbon Stock in Vegetation and Soil (tonne C)[2] | Baseline Carbon Stock (tonne C) | Target Habitat Type | Target Average Carbon Stock in Vegetation and Soil (tonne C) | Projected Carbon Stock (tonne C) | Projected Increase in Carbon Stock (tonne C) |
|---|---|---|---|---|---|---|---|
| Mature Secondary Forest | 8.9 | 194-253.6<br>Mean: 223.8 | 1991.82 | Dipterocarp Dominated Forest | 223.8 | 1991.82 | 0 |
| Young Secondary Forest | 10.7 | | 2394.66 | Mature Secondary Forest | | 2394.66 | 0 |
| Mixed Plantation Woodland | 7.2 | 111.5-162.8<br>Mean: 137.1 | 987.12 | Young Secondary Forest | | 17344.50 | 6719.25 |
| Woody Scrubland | 33.4 | | 4579.14 | | | | |
| Scrubland / Grassland | 36.9 | | 5058.99 | | | | |
| Bare ground | 2.9 | 67.5 | 195.75 | Scrubland / Grassland | 137.1 | 397.59 | 201.84 |
| | - | - | **15207** | - | - | **22129** | **6921** |

Notes:

[1] "For the baseline assessment, the various habitats recorded on the site were consolidated into three categories to align with the data obtained from our literature review."

[2] The range of carbon stock is sourced from Publication from FAO; IPCC (2019); Krisnawati et al., (2024)

**tonne C per unit time** = **Scientific Literature** (Sequestration rate multiplier) X **Field Data** (Measured quantity of habitat)


Figure 12. Carbon stock baseline and projection for the Bintan pilot. The table reports, by habitat type, area (ha), baseline and projected average carbon stock in vegetation and soil (tonne C), target habitat type, and the projected increase in carbon stock. The lower panel shows the five-pool framework (above-ground biomass, below-ground biomass, soil, woody debris, and litter) with the per-hectare stock values (tC/ha) applied to each habitat, where projected stock is derived by combining literature-based sequestration values with field-measured habitat data.

# Chapter 5

## Measuring Change: From Baseline to Uplift

An index is only useful if it can measure change. The NCi is designed around a baseline–projection–monitoring cycle that runs across a 30-year restoration timeline, a period long enough to capture meaningful ecological restoration and short enough to remain commercially tractable.

### Step 1: Establishing the Baseline

Baseline assessment is the most data-intensive phase. It establishes the starting condition of every parcel within the site across all five metrics. The baseline produces, for each parcel and for the site as a whole, a set of five normalised scores and the Composite NCi Score derived from them. Every monitoring assessment in subsequent years is benchmarked against this starting point.

Data inputs at baseline include parcel-level habitat mapping (remote sensing validated by walkover), biodiversity unit calculation through the biodiversity accounting metric, eDNA sampling for soil biota community composition, bioacoustic recorder deployment for fauna species diversity, soil sampling for organic matter content, hydrological model parameterisation, NDVI extraction for leaf area index, and field-based biomass data collection for carbon stock calculation. Each input feeds the analytical pipeline for its corresponding metric.

### Step 2: Projecting Restoration Outcomes

The projection phase defines what successful restoration looks like for each parcel over a thirty-year horizon. The biodiversity accounting metric plays a central role here. It serves not only as the source of the structural-vegetative metric within the Composite Biodiversity Index, but as the predictive engine that drives the projection across all five metrics.

For each parcel, the biodiversity accounting metric is used to model the expected successional trajectory based on the current habitat type and condition, the planned restoration interventions, and the known recovery rates for the ecoregion. This produces a projected post-restoration habitat type and condition for the parcel, and a corresponding projected biodiversity unit value. The projected habitat composition is treated as the central expected case for that parcel, the realistic restoration outcome under the planned interventions, rather than as a theoretical maximum, though on a case-by-case basis it may coincide with the ceiling.

The projected habitat composition then drives the projections for the remaining four ecosystem service metrics. The same analytical methods applied at baseline are applied to the projected future habitat: literature-based carbon stocks for the projected habitat type, expected soil organic matter values for the projected condition, hydrological model outputs for the projected habitat map, and dry deposition estimates from the projected leaf area index. The reference site provides the ceiling value for each metric, while the projection itself is the expected trajectory toward that ceiling.

Restoration projection intervals are set parcel by parcel, calibrated to the expected rate of successional change. Lower successional habitats typically transition more quickly than mature habitats, so the meaningful milestones for monitoring will differ. A scrubland parcel projected to reach young secondary forest may justify milestones at three, five and ten years; a secondary forest projected to reach a more mature forest state may instead be tracked at ten, twenty and thirty years. Milestones are documented in the parcel-level monitoring plan.

| Habitat Type | Area (ha) | Baseline Units | Post-restoration Units | Percentage Increase |
|---|---|---|---|---|
| 2 Mature Secondary Forest | 8.9 | 106.8 | 195.4 | 83.0% |
| 3 Young Secondary Forest | 10.7 | 64.2 | 213.8 | 233.0% |
| 4a Woody Scrubland | 33.4 | 133.6 | 244.6 | 83.0% |
| 4b Mixed Plantation Woodland | 7 | 42 | 55.8 | 33.0% |
| 5 Scrubland / Grassland | 36.9 | 73.8 | 245.7 | 233.0% |
| Bare ground | 2.9 | - | 5.8 | - |
| TOTAL | 99.8 | 420.4 | 960.4 | 128.4% |

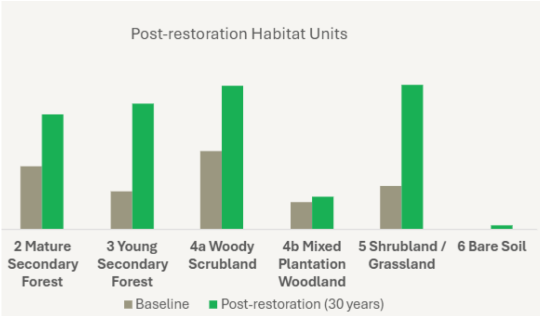



Figure 13. Illustrative baseline and projected post-restoration biodiversity units at the Bintan Pilot, by habitat type. The table reports area (ha), baseline units, projected post-restoration (30-year) units, and percentage increase for each habitat type, with the accompanying chart comparing baseline and post-restoration habitat units.

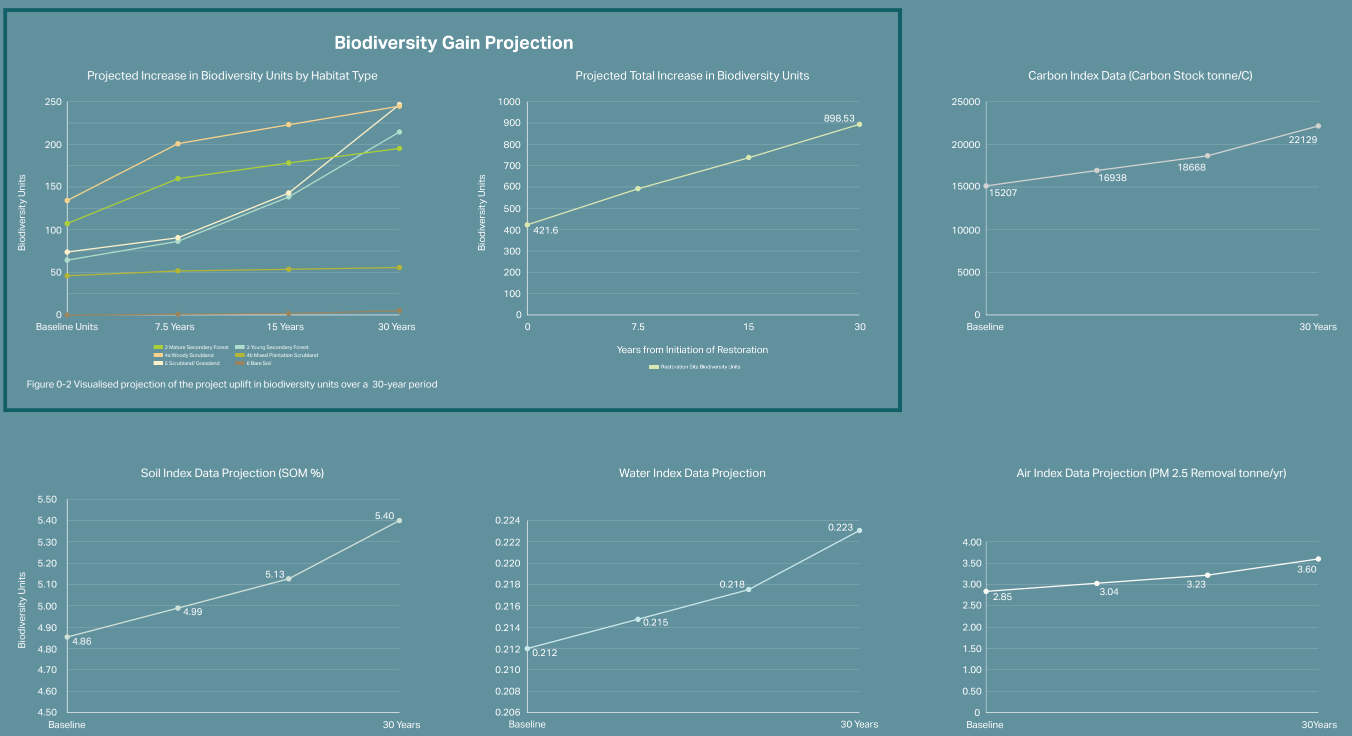



Figure 14. Natural Capital Index projections over a 30-year restoration horizon at the Bintan island Pilot Site, showing projected trajectories for: Biodiversity Units by habitat type and in aggregate (Biodiversity Gain Projection); Soil Organic Matter (%); Water Quality Index; Carbon Stock (tonnes C); and PM2.5 removal (tonnes/year). Projections are derived from baseline NCi scores and predicted successional trajectories informed by the restoration plan and monitoring framework.

## Step 3: Monitoring and Adaptive Management

The role of monitoring is to confirm that the projected uplift is occurring on schedule across all five metrics. Where the biodiversity accounting metric established the expected trajectory, the full NCi is the tool through which actual progress is tracked against it. Every monitoring cycle re-runs the relevant analytical inputs (e.g., habitat reassessment, eDNA and bioacoustic resampling, soil sampling, hydrological updates, NDVI and biomass updates) and produces a refreshed set of five normalised scores and a refreshed Composite NCi Score, at parcel level and site level wherever possible.

The frequency of monitoring is highly dependent on the expected rate of change and site-specific conditions. As a principle, monitoring should be more frequent in the years when habitats are establishing or being actively restored, and less frequent in later years where habitat maturation takes longer.

We recommend that during the first decade, monitoring runs at intervals of twelve to thirty-six months, calibrated parcel by parcel to the expected rate of habitat change. Rapidly changing habitats (e.g., early successional parcels with substantial near-term transition expected) warrant more frequent assessment than slow-changing mature parcels. From year ten onward, monitoring should run at between three- and five-year intervals as standard, with provision for additional event-triggered monitoring after disturbance (fire, encroachment, intervention adjustment) and increased frequency where adaptive management has been initiated.

Each monitoring cycle compares observed performance against the projected trajectory. Where any of the five normalised scores diverges from projection, and particularly where divergence persists across consecutive monitoring cycles, adaptive management must be considered. Adaptive management does not automatically mean intervention; it means a structured review of why the metric is lagging, whether the divergence is within expected variability, and what corrective action (if any) would bring the parcel back on trajectory. Responses range from minor adjustment of management activities to revised intervention design, to recalibration of the projection itself where the original assumption proves unrealistic for the site. Monitoring data informs not only adaptive management of individual projects, but also portfolio-level decisions governed under separate frameworks. The objective throughout is to maintain a credible pathway to the projected thirty-year outcome.

Monitoring data can be hosted on a natural capital digital twin, a visual interface that makes the five performance scores accessible to project stakeholders, investors and the public, parcel by parcel and at site level. Transparency at this layer is essential. Restoration finance depends on the credibility of the underlying data, and credibility depends on visibility.

# Chapter 6

## The Role of Biodiversity Accounting in the NCi

The biodiversity accounting metric used within the NCi methodology (Example: the Singapore Biodiversity Accounting Metric in the Bintan pilot, or equivalent regional metrics in other geographies), performs two distinct functions.

In plain terms: we predict the future habitat, and from that we predict everything else. Monitoring then checks reality against that prediction, and it is the surprises, where reality and prediction part company, that tell us the most.

In its first role, the biodiversity accounting metric is the source of the structural and vegetative metric within the Composite Biodiversity Index. It contributes one third of the biodiversity score, alongside the soil biota and faunal species diversity metrics. It does this by comparing baseline units against the parcel's projected target units.

In its second role, the biodiversity accounting metric is the predictive engine for the entire NCi projection. It is used to model the expected 30-year successional trajectory for each parcel, defining the post-restoration habitat type and condition. The four ecosystem service projections (air, water, soil and carbon) are then derived from this projected habitat composition by applying the same analytical methods used at baseline. The reference site sets the upper limit each metric can reach; the biodiversity accounting projection sets the expected trajectory toward that limit.

This dual role is deliberate. Biodiversity accounting metrics aid in the prediction of change in habitat condition. Anchoring the projection to the biodiversity accounting metric, and deriving the other four projections from the predicted habitat composition, produces a methodologically coherent forecast, one in which the five projected scores are internally consistent.

This coherence has implications for how monitoring is interpreted. If the projected habitat is realised, the four ecosystem service projections will, by construction, also be largely realised, the analytical models will produce the projected values from the observed habitat composition. The substantive monitoring question is therefore not whether the five scores rise together (they will, if the habitat transitions as expected), but whether the observed scores diverge from what the observed habitat composition would predict. Divergence between observed habitat and observed ecosystem services is the genuinely informative signal, because it reveals where the analytical models do not quite fit site-specific reality and that, in turn, is the trigger for closer investigation and potential adaptive management.

The NCi is therefore a coherence test as much as it is a measurement system. The biodiversity accounting metric is the projection anchor; the full five-metric NCi is the means by which the projection's coherence with on-the-ground reality is tested at every monitoring cycle.

# Chapter 7

## Verification and Assurance

Methodology alone does not produce investable data. The NCi is paired with independent third-party verification provided by CMA Testing, drawing on their expertise in greenhouse-gas quantification and environmental data assurance. Verification covers three layers:

- **Methodology review** — independent assessment of the analytical framework, the appropriateness of selected models, the defensibility of the reference site selection and projection assumptions, and the integrity of the biodiversity accounting metric's predicted successional trajectories. Any submitted documentation should also outline the qualifications of the team who undertook the assessment.
- **Data audit** — sampling and recalculation of baseline and monitoring data, chain-of-custody review for physical samples (soil, eDNA), and validation of model outputs against input parameters, provided by expert team from AECOM.
- **Reporting assurance** — confirmation that the reported five metrics and the derived Composite NCi Score can be reproduced from the underlying data, and that any methodological deviations from the published protocol are documented.

Verification is conducted at baseline, at each monitoring cycle, and on a methodology basis whenever the published protocol is updated. The output is an verification statement that accompanies the published NCi results, giving downstream users (corporate ESG reporting, green finance instruments, portfolio-level natural capital products) the audit trail they require.

# Chapter 8

## The Bintan Pilot in Numbers

The first full application of the NCi is the Bintan Island pilot project, established in 2024 on a 100-hectare degraded forest site within a 760-hectare study area in Indonesia's Riau Archipelago. Bintan was historically covered in dipterocarp-dominated tropical rainforest. From the 1740s onward, successive waves of plantation agriculture, logging and small-scale bauxite extraction have left most of the island in various states of degradation. Between 1990 and 2020, bare land on the island increased by 186 per cent.

The pilot site is representative of the broader challenge: a mosaic of secondary forest patches, scrubland, mixed plantation woodland and bare ground, with the dipterocarp-dominated reference state surviving only in fragments within the wider 760-hectare envelope. The site has been mapped into discrete parcels by habitat type, each with its own baseline value, restoration target and projected trajectory.

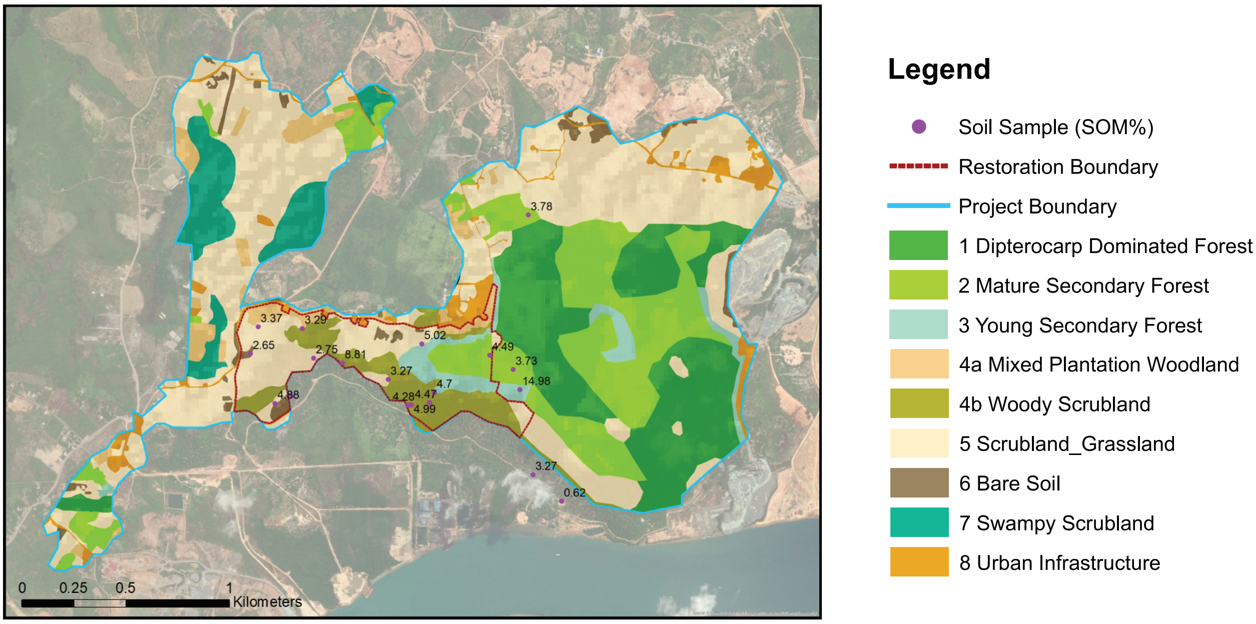



Figure 15. Habitat classification map of therestoration area, Bintan Island, Indonesia, showing the spatial distribution of eight habitat types across the project boundary and restoration boundary, with soil organic matter (SOM%) sampling locations. Habitat classes range from early successional (Bare Soil, Scrubland/Grassland) to mature closed-canopy forest (Dipterocarp Dominated Forest), reflecting the degradation gradient across the site.

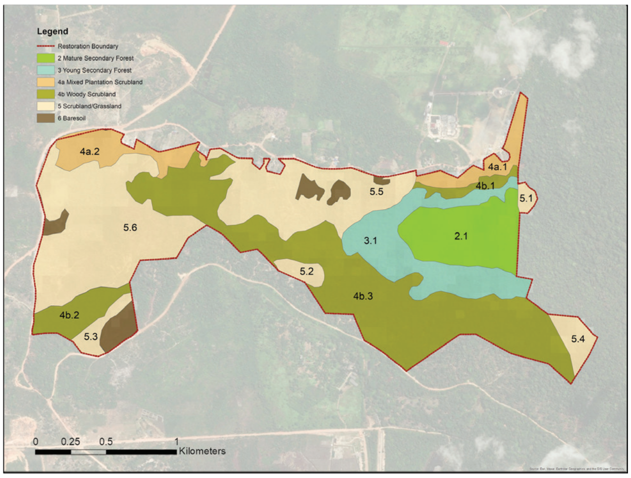
## Baseline and 30-Year Projection

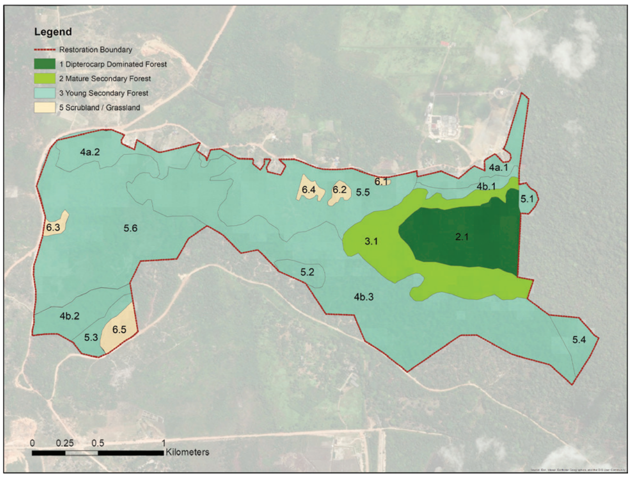
The full baseline assessment was completed in May 2025. The five NCi metrics were measured across the 100-hectare site, and a thirty-year projection was developed for each, assuming passive restoration measures supported by adaptive interventions: dipterocarp seedling planting, removal of disturbance pressure, introduction of organic topsoil where required, and engagement with local communities to safeguard the recovery zone.

| Metric | Unit | Baseline | 30Year Projection | Change |
|---|---|---|---|---|
| **Biodiversity** | SGBA units | 421.60 | 898.53 | +113% |
| **Air quality** | tonne $PM_{2.5}$/yr | 2.12 | 3.64 | +71% |
| **Water regulation** | Composite index | 0.201 | 0.223 | +11% |
| **Soil quality** | % SOM | 4.31 | 5.40 | +25.3% |
| **Carbon stock** | tonne C | 15,207 | 22,129 | +45.5% |

Table 1 — The Bintan NCi individual performance scores: baseline and 30-year projection across the 100 ha pilot site, in absolute reported units.

Each ecosystem service performance value in the vector tells part of the story. The projected 113 per cent uplift in biodiversity units reflects the transition of degraded scrubland and bare ground into native-dominated secondary forest, with portions reaching dipterocarp-dominated composition. The 71 per cent increase in $PM_{2.5}$ removal is driven by leaf area expansion as woody species establish. The 45.5 per cent carbon stock gain reflects both biomass accumulation and improved soil carbon. The smaller 25.3 per cent SOM increase indicates a recovery in soil function, which underpins the long-term resilience of the other gains.




| Habitat Types | No. of habitat parcels | Area (ha) | Biodiversity Units |
|---|---|---|---|
| 1 Dipterocarp Dominated Forest | - | - | - |
| 2 Mature Secondary Forest | 1 | 8.9 | 106.80 |
| 3 Young Secondary Forest | 1 | 10.7 | 64.20 |
| 4a Mixed Plantation Woodland | 2 | 7.2 | 43.20 |
| 4b Woody Scrubland | 3 | 33.4 | 133.60 |
| 5 Scrubland / Grassland | 6 | 36.9 | 73.80 |
| Bare ground | - | 2.9 | - |
| TOTAL | | 100 | 421.60 |

The restoration of the site can more than double the biodiversity value.

| Habitat Types | No. of habitat parcels | Area (ha) | Biodiversity Units |
|---|---|---|---|
| 1 Dipterocarp Dominated Forest | 1 | 8.9 | 195.44 |
| 2 Mature Secondary Forest | 1 | 10.7 | 149.59 |
| 3 Young Secondary Forest | 11 | 77.5 | 547.70 |
| 4a Mixed Plantation Woodland | - | - | - |
| 4b Woody Scrubland | - | - | - |
| 5 Scrubland / Grassland | 5 | 2.9 | 5.80 |
| Bare ground | - | - | - |
| TOTAL | | 100 | 898.53 |

Figure 16. Baseline and target condition habitat maps and Biodiversity Unit calculations for the restoration area, Bintan Island. Left: current baseline habitat distribution and associated Biodiversity Units by habitat parcel (total: 421.60 BU). Right: projected target condition following restoration, with habitat succession toward mature forest classes and associated Biodiversity Units (total: 898.53 BU). Restoration is projected to more than double the site's biodiversity value over the restoration horizon.

## Transparency on Pilot Constraints

The Bintan pilot was designed as a feasibility test of the NCi methodology. Four methodological constraints arose and should be disclosed.

The first relates to the habitat condition assessment. The SGBA condition criteria, designed for the Singapore context, include fauna-based sub-criteria that depend on dense reference datasets. Those datasets do not exist at equivalent density for Bintan. The Bintan condition assessment was therefore adapted to focus on vegetation, structural diversity and degradation criteria alone, with fauna assessed instead through the bioacoustic and eDNA metrics. This is a defensible adaptation but it would not be the preferred configuration where richer fauna reference data is available.

The second relates to the aggregation of the Composite Biodiversity Index. The full Tier 2 methodology specifies equal weighting of three metrics: habitat and vegetation, soil biota, and faunal acoustic community composition. In the Bintan pilot, the soil biota metric was calculated and reported but not included in the final aggregated biodiversity score, under the general provision set out in Metric 2 for situations of insufficient pristine reference data. The reason was the absence of fully pristine reference data against which to confidently calibrate the eDNA metric within the 100-hectare envelope. The dipterocarp-dominated reference fragments are within the wider 760-hectare site but not all are pristine, and reference data density for the broader ecoregion is sparse. The Bintan biodiversity index therefore runs, for this baseline, on a two-metric aggregation (habitat and vegetation, faunal acoustic composition), with soil biota carried as supporting data and the full three-metric aggregation to be reinstated at later monitoring rounds as reference data improves.

The third relates to normalisation of the four ecosystem service metrics. The Bintan ecosystem service scores were computed on absolute, literature-derived values prior to the formalisation of progress-to-target normalisation described in this paper. The absolute values reported in Table 1 remain valid as the Bintan ecosystem service performance scores; future deployments and future Bintan monitoring rounds will apply progress-to-target normalisation consistently across all five metrics. Both approaches are version-controlled so that historical Bintan data remains traceable and comparable as the methodology matures.

The fourth relates to the enhancement calculation within the biodiversity accounting metric. The Bintan biodiversity projections were generated using an earlier formulation in which the risk multiplier was applied to the retained baseline rather than to the projected uplift. The methodology described in this paper reflects the corrected formulation, aligned with the DEFRA metric structure, in which the baseline is retained in full and only the projected uplift is risk-discounted. The corrected formulation applies to all projects subsequent to the Bintan pilot. As with the other constraints, both formulations are version-controlled so that Bintan's reported figures remain traceable to the metric version under which they were produced.

***Transparency about methodological constraints is a precondition for trust, and trust is a precondition for finance. The NCi publishes its limits as openly as its outputs.***

# Chapter 9

## The Road Ahead

### Methodology Evolution

The NCi is a living methodology. Several developments are under active consideration for future iterations. Bird guild and functional trait diversity metrics offer the most promising near-term addition to the composition metric, providing a measurement of ecological function (pollination, seed dispersal, predation, nutrient cycling) that complements raw species-diversity counts. Integration is dependent on reference data availability and on validation that the additional indicator improves the index's sensitivity to true ecological recovery.

Other planned evolutions include expanded eDNA targeting (water column and air sampling alongside soil), refined LAI inputs from higher-frequency satellite imagery, and the integration of structural complexity metrics derived from LiDAR or photogrammetric point clouds. Each will be subject to the same documentation and verification standards applied to the current methodology.

### From Index to Asset

The NCi is the measurement layer. The financial layer is the Natural Capital Unit (NCU), a tokenised representation of measured natural capital performance. The NCU is not itself a regulated offset claim: it is a data-bearing instrument that conveys information about a project's natural capital trajectory, structured to sit alongside formal regulated credits (such as biodiversity units or carbon credits) without introducing double counting. Individual projects are pooled within the NCU structure, allowing portfolio-level diversification of restoration risk.

Together, the NCi and the NCU form the measurement-and-monetisation pairing that the manifesto set out to establish. The NCi makes nature recovery measurable. The NCU makes it tradable. The verification chain provided by CMA Testing makes the pairing investable. With these three elements in place, natural capital becomes what the manifesto argued it should be: an infrastructure class, with the same measurement discipline, capital access and accountability as any other.

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## About Napital

Napital is an open platform, sharing our journey, ideas, and approach with transparency and purpose. We embrace collaboration and diverse perspectives with one goal: achieving a greater good for our planet. We deliver integrated ESG pathways and Nature-based Solutions (NbS) that go beyond conventional practice—turning natural capital into measurable environmental performance through project design, implementation management, and both technical and commercial support. At the core of our methodology is the Natural Capital Initiative: an integrated framework that combines high-performance ecosystem delivery with NbS design, monitored through digital twin and blockchain infrastructure. This approach is anchored by the Natural Capital Index (NCi)—five key performance indicators (biodiversity, carbon sequestration, soil, air, and water quality)—supported by environmental data digitalisation and blockchain-based transparency. Together, these tools reliably track ecological gains and provide credible evidence of impact. To embed lasting ecological awareness across organisations and communities, we partner with universities and academic leaders—bridging research and practice to drive meaningful change.

## About AECOM

AECOM is the world's trusted infrastructure consulting firm, delivering professional services throughout the project lifecycle – from advisory, planning, design and engineering to program and construction management. On projects spanning transportation, buildings, water, new energy, and the environment, its public- and private-sector clients trust the firm to solve their most complex challenges. Its teams are driven by a common purpose to deliver a better world through its unrivaled technical and digital expertise, a culture of equity, diversity and inclusion, and a commitment to environmental, social and governance priorities. AECOM is a Fortune 500 firm and its Professional Services business had revenue of $14.4 billion in fiscal year 2023. See how it is delivering sustainable legacies for generations to come at aecom.com and @AECOM.

## About CMA Testing

CMA Testing, which was established in 1979, is a well-known third-party assurance body that specializes in testing, inspection, and certification services. With a dynamic team of professional experts, its worldwide networks have been spreading rapidly to 12 global footprints locating in Asia, the Middle East, Europe, and North America. To keep up with the fast-changing market as well as the wave of "re- industrialization", CMA Testing not only provides diversified testing services, but also assists enterprises in upgrading and transforming to cope with the future development. CMA Testing will develop diverse business solutions to respond to the needs of the market in alignment with the company's core values – A Better World, Passionately Curious and Perfectly Scaled, ensuring the safety of consumer products, enhancing the quality life of consumers and sustaining a green environment for the betterment of the community.