A nature-based solutions assessment framework integrating Indigenous biocultural and ecosystem services perspectives

An Australian example

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A nature-based solutions assessment framework integrating indigenous biocultural and ecosystem services perspectives: An Australian example

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ABSTRACT

Assessing ecosystem services (ES) indicators has become vital to measuring the condition of ecosystems and their benefits, and informing policy and businesses for appropriate conservation and investment decisions. However, the ES indicators depending on ecosystem type, and the tools and measures developed to date mostly consider ecological attributes with little relevance to Indigenous Peoples and Local Communities (IPLC) contexts. Here, together with Australian Indigenous community participants, we assess and co-develop an integrated set of ecological and socio-cultural indicators, and associated assessment tools. We reviewed relevant global literature and conducted focus group meetings with three Indigenous groups, representing Traditional (Land) Owners, senior community members and rangers in northern Australia. Our literature review identified 30 ES indicators and associated assessment tools, addressing provisioning, regulating, biodiversity and cultural services, primarily across the forest, agriculture, wetland and grassland ecosystems. Largely, biodiversity and regulating services encompassed ecological indicators rather than provisioning and cultural services. Notably, the IPLC context was not captured within the reviewed literature on indicator frameworks. The results from focus group discussions with Indigenous participants addressed this gap, describing 16 appropriate indicators (and associated measurement tools) for assessing Indigenous people's socio-cultural, ecological and economic experiences and aspirations. The proposed bottom-up, integrated biophysical and bio-cultural indicator framework empowers local communities and is useful for informing practitioners and emerging incentivising/Payment for ES schemes. Our conceptual framework is generic to adapt to any local context, and offers potential application in evolving Nature-based Solutions markets and for informing socio-economic, natural resource use management, and policy-related IPLC contexts in Australia and globally.

1. Introduction

Biodiversity and ecosystems provide ecosystem services (ES) that benefit human economies and well-being. Over half of the global gross domestic product (GDP ~ US$ 44 trillion as of 2021) is moderately or highly dependent on nature's services (United Nations Environment Programme [UNEP], 2021). In Australia, most economic sectors have a moderate to very high direct reliance on nature (about half of the Country's GDP, equivalent to AU$895 billion/yr; Australian Conservation Foundation et al., 2022). Current pathways of economic growth, mainly focusing on extracting resources for development, have already affected three-quarters of land and two-thirds of marine resources (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services [IPBES], 2019), and associated > 10 percent loss of annual global GDP, affecting the well-being of 3.2 billion people (IPBES, 2018).

Transformative actions required to mitigate biodiversity loss and protect and restore nature are emphasised by several International organisations, including IPBES, UNEP, and the International Union for Conservation of Nature (IUCN) (IPBES, 2022; UNEP, 2024). Consequently, Nature-based Solutions (NbS)/economies and related frameworks, developed appropriately, are considered a win–win solution both for ecological as well as socio-economic problems (IUCN, 2020; Sangha et al., 2024; UNEP & IUCN, 2021). In 2018, Payment for Ecosystem Services (PES) economies were reportedly worth US$ 42 billion per year (Salzman et al., 2018), and are expected to grow multi-fold in coming

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years. For the reliability, integrity and success of NbS and related economies, it is pivotal to understand and assess the current condition of biodiversity and ecosystems and their services at (a) a given space and time, and (b) improvements in subsequent time periods. To do so, we need to develop appropriate methods (indicators, measures and tools) to record and track the status and trend of ecosystems, biodiversity, and human well-being. However, most of such methods developed to date are based solely upon modern/Western science values, with little inclusion of Indigenous or local people's knowledges. This paper addresses this issue and proposes a generic framework of integrated ecological and socio-cultural indicators incorporating Indigenous community perspectives from northern Australia that can be adapted to a local context to inform ES assessments, emerging incentivising/PES schemes and related socio-economic and policy matters.

Indigenous peoples and local communities (IPLC) own and/or manage at least 32 per cent of global land and associated inland waters, and of which it is considered that 80 % is still in relatively good condition (WWF et al., 2021). About a quarter of the total carbon sequestered in tropical rainforests is on IPLC lands (Rights and Resources Initiative et al., 2018). IPLCs' stewardship and management can help achieve better conservation outcomes and deliver ES, potentially sustaining more biodiversity than state-protected areas (Stevens et al., 2024). For example, three-quarters of Australia's 272 terrestrial or freshwater vertebrate species listed as threatened under national legislation have projected ranges that overlap with Indigenous lands (Renwick et al., 2017). Emerging nature-based markets create new opportunities for involving IPLCs in protecting and restoring areas of high conservation values—but only if innovative incentivising mechanisms recognise IPLC contexts (Sangha et al., 2024).

It is acknowledged that combining biophysical elements with socio-cultural dimensions and Indigenous knowledges can significantly inform conservation actions (Potschin-Young, 2018). Linking biophysical dimensions to societal well-being outcomes can enhance the relevance of ecological information, making it more interpretable for policymakers and local communities (Goolmeer et al. 2022; Boyd et al., 2015; Perrings et al., 2011). IPLCs have diverse socio-cultural and spiritual relationships with their ecosystems and an integrated approach is required to capture their needs, values and aspirations for ecosystem management and broader NbS (Normyle et al., 2022; Sangha et al., 2015; Sangha et al., 2018). An appropriate indicator framework for IPLCs should, therefore, reflect interconnections among ecosystems, their services, and local cultures to have effective conservation and socio-economic outcomes.

To do so, this study underlines and addresses the current issues and research gaps in ES indicators and develops a generic, integrated framework incorporating Indigenous values and perspectives from northern Australia. We do so by examining:

1. the common global ES indicators and tools used to measure the state of ecosystems and ES;
2. understanding and integrating IPLC's values, indicators and tools for informing future NbS/PES schemes.

For the first step, we reviewed selected global and Australian studies that considered all three aspects, i.e. ES indicators, measures and tools. For the second step, we draw from findings of Indigenous community focus group discussions undertaken in northern Australia. Finally, we present an integrated set of biocultural and ecological ES indicators, measures and tools covering ecological/biophysical and socio-cultural domains. Our purpose is to encourage the application of similar frameworks in emerging nature-based economies (NbE), ES assessments and related socio-policy programs in Australia and elsewhere.

This paper is organised as follows:

- Section 2 outlines methods including the literature selection strategy for ES indicators, measures and tools from a global and local context, and the approach addressing focus group discussions with Indigenous groups and experts in Australia.
- Section 3 presents results including the indicators, measurable attributes and tools related to ES, identifies existing gaps, and describes the results from focus group discussions with Indigenous peoples in Australia on biocultural indicators and measures. Following, we propose an integrated indicator assessment framework including biocultural and ecological indicators, attributes and tools that can be used for NbS/NbE.
- Section 4 (Discussion and Conclusions) presents an overall context of integrating biophysical and culturally appropriate local/IPLC indicators, measures and tools and their applicability for NbS and similar socio-policy contexts.

2. Methods

ES are the direct and indirect contributions of ecosystem structures and functions—often in combination with other inputs—to human well-being, making them valuable indicators for management-relevant actions and investment about past, present, or potential future states of social-ecological systems (Burkhard et al., 2012). Typically, ES indicators represent the physical elements of ecosystems that can be quantified using appropriate tools and knowledge, to distil complex information about the ecosystem structure (e.g. extent, condition, or stock) and function (e.g. carbon storage) into simple and useful messages for decision-makers and investors to track conservation and socio-economic outcomes (Brown et al., 2014; Müller & Burkhard, 2012). The term "indicator" is generally defined as a measure or metric based on verifiable data that conveys information beyond itself (UNEP-WCMC, 2011). Indicator-related *measures* constitute a standard form of quantitative and qualitative units to express the size, amount and degree relevant to the purpose. Several recent studies (Cortina & Porras, 2018; Grima et al., 2023; Porras & Chacón-Cascante, 2018; van Oudenhoven et al., 2018) have provided a comprehensive list of indicators to assess ecosystem condition and ES; however, they do not consider IPLC contexts. This leads us to consider developing an Indicator assessment framework integrating Indigenous biocultural and ES perspectives, following the steps outlined below (Fig. 1):

2.1. Step 1 – A systematic review of global ES indicator studies

A systematic review of peer-reviewed articles or book chapters on ecosystems and ES indicators was conducted using Google Scholar, Web of Science and Ecological Indicators (journal) databases (Table 1). Our main criteria for selecting articles were: 1. studies primarily focusing on natural terrestrial ecosystems (i.e. forests, savannas, woodlands, and grasslands); and 2. collective consideration of ES indicators, measures and tools. In the first step, the search term "ecosystem services indicators" in Google Scholar and Web of Science (from 2015 to 2024) resulted in a broad collection of 6,642 papers published on ES indicators. In the second step, we used the Boolean "ecosystem services indicators" AND "measures" AND "tools", which limited the number of articles to 17. This led us to perform a targeted search in the journal "Ecological Indicators", which publishes the most extensive research on "the monitoring and assessment of ecological and environmental indicators with management practices". We also reviewed the grey literature, such as Indigenous Protected Area (IPA) plans. Mostly these plans are developed by experts in consultation with local groups, typically following standard formats and largely omit *Country*-related Indigenous indicators and tools except for a few recent initiatives on developing Healthy Country/IPA plans by Bush Heritage Australia (https://www.bushheritage.org.au/places/arafura) and the Conservation Coaches Network (CCNet; https://sites.google.com/view/cop-indigenous-cs-projects/resource-library).

Finally, the results obtained from the three databases were screened by title and abstract for the initial selection of 60 papers that covered ES

Goal: To develop an integrated biocultural and ES indicator assessment framework.

Methodological steps taken to develop the framework:

Step 1. A systematic review of global ES indicator studies to identify the existing ES indicators and gaps

Step 2. Understanding, developing and incorporating IPLC's indicators — Focus group discussions with Indigenous peoples from northern Australia

Step 3. Develop an integrated assessment framework to inform NbS

Fig. 1. An outline of the steps to develop an integrated assessment framework.

Table 1
Global literature search on ecosystem services indicators, measurements and tools.

Screening steps	Google Scholar	Web of Science	Ecological Indicators (ScienceDirect) (2015–2024)
"Ecosystem services indicators"	910	5602	130
"Ecosystem services indicators" AND "measures" AND "tools"	0	167	83
Title screening	27	76	81
Abstract screening	20	23	17
Final articles for review including indicators, measures and tools together	27		

indicators, tools and measures. From a subsequent reading of those papers, we selected 27 papers that explicitly and collectively mentioned indicators, measurements/attributes and tools. The final analysis included peer-reviewed articles and institutional documents. We also surveyed published literature from Government and Non-Government Organisations involved with ES assessment, mainly from Australia (such as Bush Heritage, Accounting for Nature, and Healthy Country/ IPA plans by local Aboriginal Corporations, and others). Articles on marine, coastal, and urban ecosystems were excluded due to our primary focus on terrestrial systems.

Selected papers were reviewed following a set of attributes/characteristics for data extraction focusing on:

- Ecosystem types: forests, agriculture, pasture/grassland, and wetlands.
- ES: provisioning, regulating and cultural services.
- Indigenous perspectives: consideration of Indigenous values/ concepts
- Indicator types: socio-cultural, economic, and ecological indicators including species richness, tree canopy cover, water quality, carbon stock, etc.
- Indicator measurements: quantity, area, or other units.
- Methods/tools to measure indicators: field surveys, Geographic Information System (GIS) applications, and other relevant assessment tools.
- Scale of indicator assessment: plot to ecosystem, landscape, and regional levels.

2.2. Step 2 – Focus group discussions (FGDs) with Indigenous groups – northern Australian case studies and analysis of key Australian studies targeting NbS/NbE

2.2.1. FGDs

During 2023–2024, we held three focus group meetings with three Indigenous groups represented by Traditional (Land) Owners, senior community members, and rangers, to discuss local perspectives on assessing the state and trends in the condition of their respective *Countries*—a common term used for Indigenous clan lands in Australia to which people have familial connections with, involving cultural obligations (following Sangha and Rusell-Smith 2017). A clan represents a group within a community having specific cultural rights, duties and responsibilities. We had two groups from the Northern Territory (NT) and one from north Queensland (QLD). These groups were selected based on their interest in participating in the project and the work that these groups have already done in IPA planning, monitoring and evaluation. Our discussions were informed by respective recently conducted strategic land management planning documents (e.g. Arafura Swamp Rangers Aboriginal Corporation [ASRAC], 2017; Djabugay Aboriginal Corporations, 2019; Mimal Land Management Aboriginal Corporation, 2017). In addition, the previous work by scientists in the region (Austin et al. 2017, 2018; Bush Heritage Australia; and others) on monitoring, evaluating, and reporting for IPA/Healthy Country Plans has directly informed this research, as mentioned in Section 2.1. Here, we extended that work to target indicators applicable to NbS/economies.

After reviewing each group's plans and monitoring documents, we prepared a draft list of indicators that each group had identified for their *Country's* natural assets and trends over recent years (from 2013 to 2023). We used this list as a trigger to initiate discussion on indicators that group members would like to use for assessing the condition of their *Country*, how they might measure/assess them, and what assessment tools they might apply.

Each focus group comprised 5–10 participants. Using maps, we identified core ecosystem types (e.g. savannas, woodlands, wetlands, rainforests/jungles, rocky areas and special places) describing each group's land/*Country*. For participants, 'ecosystem' correlates broadly with different *Country* types such as savanna *Country,* rocky *Country,* etc. Semi-structured questions were used to gather information on the condition and trend of *Country*/ecosystem types, the most important indicators for each *Country* type, and ranking of selected indicators for each *Country*. This information from different groups was then collated to develop an integrated Indigenous biocultural and ES framework.

2.2.2. A review of key Australian studies targeting NbS/NbE

In Australia, with recent and fast developments for nature-based economies (Australian Government 2025), several private or Non-Government Organisations (NGOs) have developed their own set of indicators and tools to assess the state of ecosystems and their services for marketing purposes. We performed a targeted analysis of reports published by key organisations such as Accounting for Nature (AfN), GreenCollar, and Bush Heritage.

2.3. Step 3 – Develop an integrated assessment framework to inform NbS

Based on the analysis of ES indicators from global studies (step 1) and Indigenous case studies from northern Australia (step 2), we identified gaps in existing information and developed a concise list of bio-cultural indicators describing IPLCs' socio-cultural, ecological, and economic values associated with different ecosystems/*Country*, and of pertinent methods and tools identified for their measurement. We contend that this proposed integrated list of indicators, related measures and tools offers the first unique indicator assessment framework addressing IPLC contexts and priorities. This framework could be adapted and applied to any local context depending on community values in relation to their natural landscape.

3. Results

3.1. A systematic review of global ES indicator studies

Measurable attributes and methods/tools were analysed from 23 pertinent global and four Australian studies focusing collectively on ecological indicators. Table 2 summarises the standard/common indicators for selected ecosystem types, related measurable attributes/measures and tools (see Appendix 1 for details). From these 27 studies, 30 indicators were identified covering provisioning, regulating and cultural ES across forest, agriculture, pasture and wetland ecosystems. Biodiversity-related indicators were most commonly identifed, with over half focusing on vegetation/flora and fauna categories. Depending upon the indicators, often the provisioning services were measured in quantity/units such as bush harvest, timber or fuel wood per unit area. Regulating services-related indicators were measured by applying diverse measures such as species richness, per cent canopy cover or biomass per unit area. Likewise, cultural indicators were measured by numbers of culturally significant sites, numbers of people visiting those sites, and the number and types of activities that people perform. The most frequently mentioned tools for measuring indicators included surveys, aerial imagery/GIS applications, photographs, observations, and interviews (Table 2). Studies often applied multiple tools for assessments; for example, combining surveys, transects, plots, camera traps, and photographs, along with a spatial approach.

Of these 27 studies, only three (Jackson et al., 2011; Russell et al., 2021; Sutherland et al., 2016) included Indigenous peoples' contexts when assessing the condition of wetland/forest ecosystems.

3.2. Findings from Australian case studies

We report results from the Australian case studies in two parts:

1. Focus group discussions conducted with Indigenous groups across northern Australia
2. Findings from key Australian organisations targeting NbS/NbE

3.2.1. Focus group discussions with Indigenous groups

All participating Indigenous groups recognised that provisioning services, such as the availability of 'bushtucker' (i.e. native bush food used by Indigenous people in Australia) plants and animals, represent key indicators of the state of their *Country*. They mentioned the flowering times, and healthy seedling regeneration of specific plants for harvesting, and the healthy condition of animals for hunting as key attributes for assessing the condition of various *Countries*/ecosystems. For instance, the abundance of specific fire-sensitive, cypress pine (*Callitris intratropica*) seedlings in savannas, sacred species of palms (*Corypha elata*) in swamps, and key animal species (emus in savannas and woodlands, cassowaries in the rainforests of north Queensland) were considered as important indicators for describing the health of respective ecosystems. Regarding water bodies, the cover of water lilies (*Nymphaea macrosperma*), and the colour and taste of water, are considered measurable attributes for assessing the condition of the freshwater/wetland ecosystems. One participant shared her view on assessing the condition of water bodies as:

"*Water lilies are a good indicator of healthy waterways and serve as food for fish and animals. When we see dragonflies on water lilies, it means a thriving ecosystem. The presence of water lilies on top of the river and billabong indicates their healthy condition. If there are no bush tucker plants growing around the edges of the water, we know that the area is not in good condition*".

Indigenous participants also reported that the application of appropriate fire management is a common indicator of the state of their *Country*. From local community perspectives, storytelling is reported as an important cultural indicator to describe social connections with *Country*. An Indigenous participant from the NT shared this experience about storytelling:

"*Story telling is the most important aspect as it relates to different songlines. Stories are everywhere, from animals to plants to water in the swamp. All the animals have songlines and the number one is "crocodile story". Story exists about how the freshwater feeds the river up and sends one line up, and that forms the swamp. This is like a mother and child relationship*".

In terms of how to measure the above-mentioned indicators and what tools to use, participants suggested a combination of cultural and scientific tools including observations, seasonal calendars, transect surveys, hunter-gatherer surveys, water testing, and fire mapping. Participants reported that observations of land and water systems following seasonal calendars, organising cultural camps, and photographic and video recordings have already been applied to date. Participants suggested a variety of appropriate assessment tools, for example: water testing tools to measure water quality or wetland condition; fire mapping using the Northern Australia Fire Information website (www.firenorth.org.au) for assessing appropriate seasonal fire management; and walking/transect surveys to measure the health of specific plants, presence of bushtucker and particular vegetation structure.

In relation to measurement tools, an elderly Indigenous participant shared her view:

"*We may not be scientists, but we can observe that plants are regrowing along the riverside. There is local and cultural knowledge to know the presence of certain plants and animals to check the land and water conditions. We visually see and believe by applying our cultural understanding to read plants and animals while rangers and scientists may rely on counting and measurements for their assessments. We can tell a complete story by combining both cultural knowledge and scientific methods. Two-way monitoring is about more than just counting; it's about understanding quality and cultural things that may not be right or captured through numbers alone*".

Another senior Indigenous participant shared their monitoring experience:

"*We can use star pickets with a transect to check the health of the rainforest, from the edge of the jungle inward, to see if it is in a normal healthy state. We take photos before and after a fire to measure whether the jungle is coming back (regenerating), or if the fire has caused damage. On plains Country, we monitor how much spear grass and kangaroo grass is coming back after a big fire. Through hunting and gathering, we observe the abundance of wallabies and share stories. We also take photographs and* videos *to capture stories about fish. Hunters can tell their stories while involving their families*".

A senior ranger and traditional owner suggested the importance of bio-cultural indicators:

"For our people, land, culture and country are never separate… This land is our supermarket and our university. We never take too much, just a little, and then leave some behind. Our people are surviving on this land so we must protect it."

(See Appendix 1 for details).

Table 2
Studies combining ES indicators, measures and tools identified from the global literature (Bush Heritage Australia & Climate Friendly, 2023; Butler & Queensland Government, 2020; Norton et al., 2016;) (Appendix 1 for details).

Ecosystem services	Ecosystems (Agriculture, Forest, Pasture, & Wetland)	Indicators	Measurements	Tools
Provisioning	Agriculture & Pasture	Crop yield	Amount of harvest (kg/ha/yr), Normalized Difference Vegetation Index (NDVI)	Farm survey, Aerial/satellite imagery and GIS
		Forage provision	Amount of aboveground biomass that can be harvested (tons of matter/ha/yr)	Aerial/satellite imagery and GIS
	Wetland	Wild plants in riparian and floodplain areas	Number/ha, Percent cover	Survey, Photograph
		Wild game hunting and aquatic materials (e.g. fish, turtle) harvested for consumption	Number of kills/ha/yr, Quantity (kg/ha/yr)	Survey, Seasonal calendar
	Forest	Wood/timber available for harvesting	Amount of wood/timber (m^3/ha/yr)	Plot survey, National forest inventory
		Wild plant materials	Abundance, Percent cover of different berry providing species (*Rubus* sp., *Vaccinium* sp., *Gaultheria shallon*)	Plot survey
Regulating and Biodiversity	Forest	Species richness (vegetation)	Species count (trees, shrubs, grass and forbs/other species)	Plot survey
		Species richness (fauna)	Species count (native and introduced vertebrates)	Wildlife camera trap, Plot survey, Transect survey
	Agriculture	Large trees	Number of living trees above diameter at breast height (DBH) per hectare	Plot survey, Aerial/satellite imagery and GIS
	Agriculture, Forest	Tree canopy height	Median/average height (m) of ecologically dominant layer	Clinometer, Stick or pencil, Plot survey
		Canopy cover	Percent canopy (trees and shrubs)	Aerial/satellite imagery and GIS, Step-count method, Transect survey, Photopoint
		Recruitment of dominant canopy species	Proportion of regenerating species with stems less than 5 cm at DBH	Plot survey, Photopoint
		Length of woody debris (lying timbers)	Total length (m/ha) of fallen logs above 10 cm diameter and 0.5 m in length	Plot survey, Transect survey, Photopoint
	Forest	Dead tree biomass	Biomass of dead trees > 12.5 cm DBH (Mg/ha) [habitat for raptors and cavity nesting birds]	Transect survey
	Agriculture, Forest, Pasture land	Organic litter cover	Percent fine and coarse organic material (fallen leaves, twigs and branches < 10 cm diameter)	Plot survey, Photopoint
	Agriculture, Forest	C storage	Aboveground tree biomass (t C/ha) Soil C content at different soil depths (Mg C/ha)	Transect survey, Aerial/ satellite imagery and GIS
	Agriculture, Pasture land	Native perennial grass cover (palatable, productive perennial species)	Average percent of native grass cover	Plot survey
	Agriculture, Pasture land	Non-native plant cover	Average percent cover of non-native/exotic species (unpalatable)	
	Agriculture, Forest	Vegetation configuration	Percent of remnant vegetation Percent of native vegetation regrowth within 1 km radius of the survey site	Transect survey, Aerial/ satellite imagery and GIS
	Agriculture, Forest, Pasture land	Soil condition	Chemical fertility (use of organic matter, p^H, N and macro/ micro-nutrients) Moisture content, porosity (bulk density/particle density ratio), and water retention curves at different tensions, aggregate stability, bulk density, texture, resistance to penetration, and infiltration Visual separation of soil macro-aggregation (> 4 mm) Count of termites from soil blocks	Transect survey, Soil sampling
	Wetland	Wetland condition	Level of temperature (^{o}C), pH and electrical conductivity (μS)	Hand-held Palintest Micro 800 water quality meter
			Turbidity Nephelometric Turbidity Units	Hanna portable turbidity meter
			Percent grass/bare ground cover Percent feral damage/flat ground	Transect survey
			Total number of Micro-invertebrates	Mesh net
Cultural	Wetland	Recreational activities	Numbers and type of activities (walking, camping)	Survey/Interviews with local authorities
	Agriculture, Forest, Pasture, Wetland	Landscape quality	Experience with landscape features (water, rivers, streams, grassland, woodland and trees)	Survey, Mapping
	Wetland	Sacred, religious and spiritual sites	Number of sites	Survey/Interviews with local authorities
	Traditional *Country*	Visiting *Country*	Number of people visiting *Country* per year	Interviews with local authorities
		Ceremony attendance	Number of people participating in ceremony per year	Oral story, Video, Photograph
		Formal and informal education	Number of education/learning activities per year	Interviews with local authorities,
	Agriculture, Forest, Pasture, Wetland	Scientific studies on flora and fauna, including emblematic species	Number of studies	Interviews of experts
	Forest, Wetland	Flora and fauna of symbolic, mythic or totemic significance	Numbers of species, Exceptional quality of tree (diameter) for carving	Survey/Interviews with local authorities
	Forest	Habitat for iconic/emblematic fauna	Number of thick canopy branches potential for habitat	Observations

Source: Accounting for Nature, 2023; Austin et al., 2018; Birkhofer et al., 2018Clec'h et al., 2016; CO2 Australia Limited, 2023; Duran-Bautista et al., 2020; Elmer, 2021; Grunewald et al., 2016; Jackson et al., 2011; Jullian et al., 2021; Ma et al., 2019; Martínez-Jauregui et al., 2019; Nel et al., 2022NSW Biodiversity Conservation Trust, 2023; Ondei et al., 2021; Pastor et al., 2022; Paula et al., 2023; Rossini et al., 2022; Russell et al., 2021; Shoo & Sinclair, 2020; Stanik et al., 2018; Sutherland et al., 2016; Taylor, 2021; Tiemann & Ring, 2022

3.2.2. Findings from key Australian organisations targeting NbS market/ NbE

In Australia, Accounting for Nature (AfN), Bush Heritage, and GreenCollar are key private organisations developing ES indicators, measures and tools for the emerging Nature Repair Markets. The evolving Australian Nature Repair Market equates to PES or NbS/NbE in other parts of the world (Australia Government 2023). We reviewed the ES indicators/tools developed by the above three prominent organizations. These indicators and tools are largely developed using existing datasets and expert knowledge.

AfN provides a list of methodological studies available for specific ecosystem condition assessments to inform policy and decision-making (https://www.accountingfornature.org/method-catalogue) (Table 3). Some State environment departments (e.g. NSW Biodiversity Conservation Trust) have also developed methods to assess the condition of ecosystems. The set of indicators, measures and tools collectively serve as 'methodologies' that can be registered with the Australian Government and are considered valid and reliable to attract investment in nature.

The selected studies predominantly focus on ecological indicators and tools for vegetation / habitats rather than on fauna (Table 3), with little consideration of Indigenous values. The common vegetation indicators fall within three categories: structure, i.e. large trees, canopy height, canopy cover, etc.; function, i.e. recruitment, organic litter cover, native grass, etc.; and configuration of remnant patches in the landscape (Table 3). Biodiversity indicators relate to species richness (flora – trees, shrubs, grass, forbs; fauna – native and introduced species). Assessment tools for vegetation indicators include plot (quadrat) and transect surveys, analysis of aerial imagery using GIS and camera trapping for fauna survey. Individual indicators can be assessed and aggregated to assess the condition of assets (native vegetation, soil, rivers, fauna, estuaries, etc.) for achieving a certified 'environmental account' — a unit that can be traded in the market.

3.3. Integrated indicator assessment framework

To develop effective mechanisms and deliver both conservation and socio-economic outcomes for NbS/NbE, there is an evident need is to integrate communities' socio-cultural values with ecological indicators. Here, based on above studies, we provide an integrated list of 16 indicators (bio-cultural indicators), related measures and tools that help assess the condition of *Country* (or assets related to ecosystems), and people's socio-economic outcomes.

The first domain of indicators relates to broader socio-cultural dimensions—'Healthy People and Culture'. This includes indicators such as storytelling, ceremonies on *Country*, people living on outstations, participation of different clan groups, jobs on *Country*, learning on *Country*, mapping and conservation of rock art and burial sites and access to *Country* (Table 4).

The second domain of indicators relates to broader cultural-ecological attributes—'Healthy *Country* and People'. This includes indicators mainly related to the condition of *Country*/ecosystems reflecting observations about appropriate fire management, presence of specific plants and their flowering seasons, bushtucker and fauna.

This indicator framework, comprising ecological, cultural, and socio-economic indicators forms the foundation when developing NbS/PES schemes for Indigenous estates. Indicators are required to report on improvements for any NbS/PES project activities. The proposed integrated framework, with indicators, measures and tools, will help the project applicants/land managers to report themselves, reducing the implementation costs while recognising their place-based traditional knowledge. Moreover, the cultural and socio-economic indicators ensure the continuity of management practices and related knowledges through stories and ceremonies, and offer an advantage for the investors to deliver on tangible socio-economic as well as ecological aspects. The framework can be adapted to local situations (e.g. type of cultural activities, ceremonies, specific bush plants, etc.), ensuring the integration of local knowledge, and can be applied at any local scale. Such local-scale information can be further aggregated at the regional and national levels. This framework informs the Nature Repair market in Australia and similar initiatives elsewhere.

4. Discussion

This paper provides a collective overview of ES indicators, measures and tools currently applied globally to assess the state of ecosystems, identifies gaps, and underlines the importance of addressing Indigenous socio-cultural perspectives—critical for IPLCs' involvement in land management. We further propose a unique, ground-up, integrated indicator assessment framework to inform emerging NbS and related market opportunities. The proposed framework is generic, illustrating examples of the type of indicators that could be adapted and applied from a community perspective. For example, bush food is an important indicator but the type of plant/animal species can vary for different communities depending upon the landscape. We emphasise that consideration of IPLCs' sociocultural values and related attributes is pivotal to effectively engaging local communities and developing affordable, cost-effective NbS/market-based mechanisms.

To date, global studies have increasingly provided comprehensive lists of ES-related indicators, while only a few mention specific measurement attributes and tools. ES assessments are now conducted by many countries across the globe, typically using biophysical indicators and related tools, and measurements (https://www.ecosystemassessments.net). Although some studies mention the role of surveys or spatially explicit tools to measure ecosystem cultural values, their application is confined to specific aspects of the landscape, such as mapping of historical land use, without addressing broader IPLC contexts (Stanik et al., 2018). A recent study in the Kimberley, WA, with Yawuru people by Normyle et al. (2024) suggests incorporating Indigenous cultural values in the System of Environmental-Economic (SEEA) framework, but the indicators for those values are yet missing. Additionally, the SEEA frameworks are mainly targeted to inform governments on the importance of Natural Capital and do not extend to NbS. In this study, we develop an integrated indicator assessment framework for NbS that is relevant to the aspirations of north Australian Indigenous people (Table 4). This framework particularly incorporates socio-cultural and ecological dimensions and can be adapted by different communities depending upon their respective ecosystem/*Country* values. Moreover, this framwork directly informs policymakers and practitioners for SEEA and other socio-economic systems.

To advance the integrated framework (Table 4), we emphasise the importance of IPLCs' capabilities (i.e. people's local, fine-scale, knowledge and skills) for managing their lands/ecosystems (following Sangha & Russell-Smith, 2017; Sen, 1999). Many IPLCs have retained and practised their traditional capabilities that can be realised through appropriate opportunities, such as NbS/NbE, which are increasingly the focus of recent global initiatives for restoring, managing, and protecting nature (Convention on Biological Diversity [CBD], 2022). To achieve effective conservation outcomes, nature-investment models need to prioritise consideration of utilizing and enhancing IPLC capabilities and achievements (i.e. *functionings* following Sen's Capability Approach-1993, 1999)—management of land/sea ecosystems (explained below in

Table 3
List of indicators, measures and tools summarised from key Australian agencies' published methodologies for the assessment of ecosystem condition.

Ecosystem services/ Biodiversity	Ecosystems	Indicators	Measures	Tools
Biodiversity (flora)	Agriculture, Woodland/ Forest, Pasture land	Vegetation configuration	Percent native remnant vegetation and regrowth	Aerial/ satellite imagery and GIS
		Large trees (including habitat trees)	Number of living stems per hectare with a DBH equal to greater than the DBH threshold	Plot/Transect survey
		Species richness of tree canopy and shrub layer species (including foraging trees)	Number of species	Quadrat survey
		Tree stem size structure (density by size class, or height variability)	Number of trees of different size classes	Aerial imagery and GIS/Plot/ Quadrat survey
		Species cover (trees, shrubs, herbaceous, or cryptogam)	Percent	Aerial/ satellite imagery and GIS, Quadrat survey, Visual estimate
		Tree canopy/ sub-canopy height	Average height	Clinometer/ stick or pencil method, Aerial/ satellite imagery and GIS mapping
		Tree canopy/ sub-canopy cover	Percent steps/length under canopy	30 mm Step-count method/ Transect, Photograph, etc.
		Tree canopy health	Percent standing trees $\geq$ 10 cm at DBH with different levels of canopy loss	Quadrat survey
		Basal area or biomass of trees	Cross-sectional area (m^2/ ha) or dry mass (tonnes per ha)	Plot survey
		Species recruitment	Percent cover, Number of species per hectare	Aerial imagery and GIS, Plot survey
		Organic litter ground cover	Percent litter cover	Quadrat survey
		Perennial grass cover	Percent grass cover	Quadrat survey
		Coarse woody debris, Fallen logs	Percent, Length (m)/ ha	Aerial imagery and GIS/Quadrat/ Plot
Biodiversity (fauna)	Agriculture, Woodland/ Forest, Pasture land	Species condition, e.g. Koala (*Phascolarctos cinereus*)	Proportion of trees recorded with Koala scat presence	Spot Assessment Technique
		Species richness (mammal)	Number of species observed	Wildlife camera trap

Source: Bush Heritage Australia and Climate Friendly, 2023; Butler and Queensland Government, 2020; Elmer, 2021; NSW Biodiversity Conservation Trust, 2023; Rossini et al., 2022; Shoo and Sinclair, 2020; Taylor, 2021

Fig. 2). As illustrated in our proposed framework (Table 4; Fig. 2) including a dimension on 'Healthy People and *Country*', better management of ecosystems delivers better well-being outcomes for IPLCs (i.e. *utility* for people as per Sen's Capability Approach) where the health of *Country* is intrinsically a part of people (Sangha et al., 2021; Sangha & Russell-Smith, 2017).

To effectively implement NbS/NbE opportunities, lists of ES indicators required to show improvements for investors need to be such that their measurements and related tools are relevant, cost-effective, reliable, and simple to apply for land managers with little external assistance (Chan et al., 2017; Sangha et al., 2024). Our proposed indicator assessment framework particularly includes biocultural as well as ecological indicators that Indigenous participants relate to and apply using a combination of traditional and Western or modern tools (here, we define traditional knowledge as a cumulative body of knowledge and practices that are handed down through cultural continuity, and Western or modern knowledge that is typically generated in universities, research institutions and private firms). Most indicators developed to date, and as used in the Australian market to assess ecosystem condition (e.g. AfN, GreenCollar, Bush Heritage), omit consideration of cultural perspectives and typically involve high transactional costs due to reliance on external expertise for assessment (Russell-Smith et al., 2024; Sangha et al., 2024).

Our biocultural indicator assessment framework reflects the interconnectedness of people with their lands (Austin et al., 2017; Campion et al., 2023), contrasting with the Western/modern approach which often emphasises single species counts or species richness in isolation of human values (Austin et al., 2019). Application of biocultural indicators has earlier been proposed by Austin et al. (2017) but in the context of reporting and monitoring the condition of *Country,* not in lieu of NbS economies. The Indigenous groups that participated in this research advocated for measuring the presence of culturally significant species as a more meaningful indicator to track biodiversity and ecosystem health—in line with the argument for recognising culturally significant species and Indigenous-led management (Goolmeer et al. 2022). This can allow Indigenous communities to apply locally relevant tools, i.e. qualitative measurement scales, such as "none/few/plenty" or "poor/okay/healthy", or use of traditional food calendars to track flowering and harvesting of bush food (ASRAC, 2021). Traditional tools can complement Western/modern methods, such as vegetation plot surveys, photos/ videos and wildlife camera trapping. Such a combined approach offers the advantage of creating a bridge between traditional and Western/modern knowledges, and enables Indigenous-led biodiversity monitoring and reporting to achieve both socio-cultural and conservation outcomes.

An important aspect of the proposed indicator assessment framework

Table 4
Biocultural indicators, related measures and tools.

Indicators		Measures		Tools
Healthy People and Culture	Participation of different clans Jobs on *Country* Learning on *Country* Ceremonies on *Country*	• Number of clans participating • Number of people employed • Number of children knowing *Country* • Number of people including young participants	Up Down	Photographs, Cultural camps, employment on *Country*, Video records of stories about plants, animals & rivers
	Access to *Country*	• Physical condition of infrastructures (e.g. access tracks)		
	People on outstations	• Number of people Presence of effective leadership		
	Story telling Mapping and conservation of rock art and burial sites	• Elders telling the story • Numbers/Percent of sites mapped and conserved Condition of rock paintings	Poor Fair Good	Photographs, Video records
Healthy *Country* and People	Fire management	• Percent area of appropriately managed habitat Trend of 'right-way fire' Right people undertaking right-way fire management	Up Down	Fire mapping (NAFI; https://www.firenorth.org.au), Transect surveys (walked, driven, flown)
	Condition of specific plants (e.g. yams, fire-sensitive, sacred species)	• Abundance of seedlings/ regeneration	None Few Plenty	Observation, transect surveys (walked)
	State of rainforest/jungle patches	• Vegetation structure Condition of fire-prone margins	Poor Okay Healthy	Transect surveys, Photopoint monitoring, GIS mapping
	Specific bushtucker plants	• Abundance of plants flowering and fruiting Amount of bush tucker	None Few Plenty	Seasonal calendar, Observations, Transect surveys
	Specific grasses	• Abundance of target native grasses and per cent cover	Poor Okay Healthy	Observations, Transect surveys
	Availability of specific animals	• Abundance of culturally significant species	None Few Plenty	Observations, Hunter-gatherer surveys, Camera trapping
	Condition of water bodies	• Water lily (*Nymphaea* spp.) cover Water cleanliness, smell and taste Water temperature, oxygen, turbidity, pH	Poor Okay Healthy	Observations, Transect surveys, Photographs, Water testing kit
		• Presence of fish, water birds	None Few Plenty	Hunter-gatherer surveys
	Condition of sea/salt water bodies in coastal areas	• Presence of sea food with right mouth colour and fat on liver at the right time Presence of plants changing leaf colour and flowering at right time	None Few Plenty	Seasonal calendar, Observations, Hunter-gatherer surveys, Photographs, Video records
	Condition of *Country* including water bodies on land in relation to weeds and pests	• Presence of feral animals (e.g. buffalo, pigs, cane toads, etc.), and weeds (e.g. Gamba grass, Mimosa, etc.)	Up Down	Transect surveys, Photopoint and targeted monitoring, GIS mapping

Source: Focus group discussions (2023-2024)

is that place-specific cultural activities such as camping, ceremonies or storytelling are important for intergenerational knowledge transfer regarding plant and animal identification, having relationships with, and detecting changes in the landscape, going beyond mere measurement of species abundance (Austin et al., 2017; Campion et al., 2023). This means not only access to land but also involvement of the right individuals—those with the appropriate knowledge, skills, and cultural understanding—is critical for the effective management of *Country* (Campion et al., 2023).

The key limitations of the proposed integrated ES indicator framework include a lack of typically quantifiable measures, robustness and reliability, especially for investors who are mainly interested in tangible outcomes. For this, a selection of appropriate reliable tools to reflect performance is quite important, and 'hybrid' tools could be designed using both traditional and Western knowledge systems, applying digital techniques such as GIS, customised photo software (with location and date specification), etc. Verification of socio-cultural indicators for ecosystems/*Country* assessment can be tricky as different clans may have different value sets and external parties may not have relevant cultural knowledge. Another limitation could be bias, subjectivity and inaccuracy in measurements, which can affect the success of NbS/NbE. Genuine implementation of the framework, with collective community-based assessment, can help eliminate such biases and subjectivity. In our study, we acknowledge the potential bias for selecting three communities given the diversity among different cultural groups in the north. However, based on our experience working with Indigenous groups over $>$ 15 years, we have tried to develop a generic framework that can be adptated to specific biocultural values, at any local and regional scales.

To date, in Australia, Indigenous-led greenhouse gas emissions abatement projects have incorporated traditional and Western/modern knowledge systems to effectively deliver climate-related NbS (Edwards et al., 2021; Russell-Smith et al., 2013). Expansion of such integrated approaches in Australia at least is timely given opportunities associated with emerging complementary biodiversity or nature credit markets (Indigenous Land and Sea Corporation, 2022; Australian Government

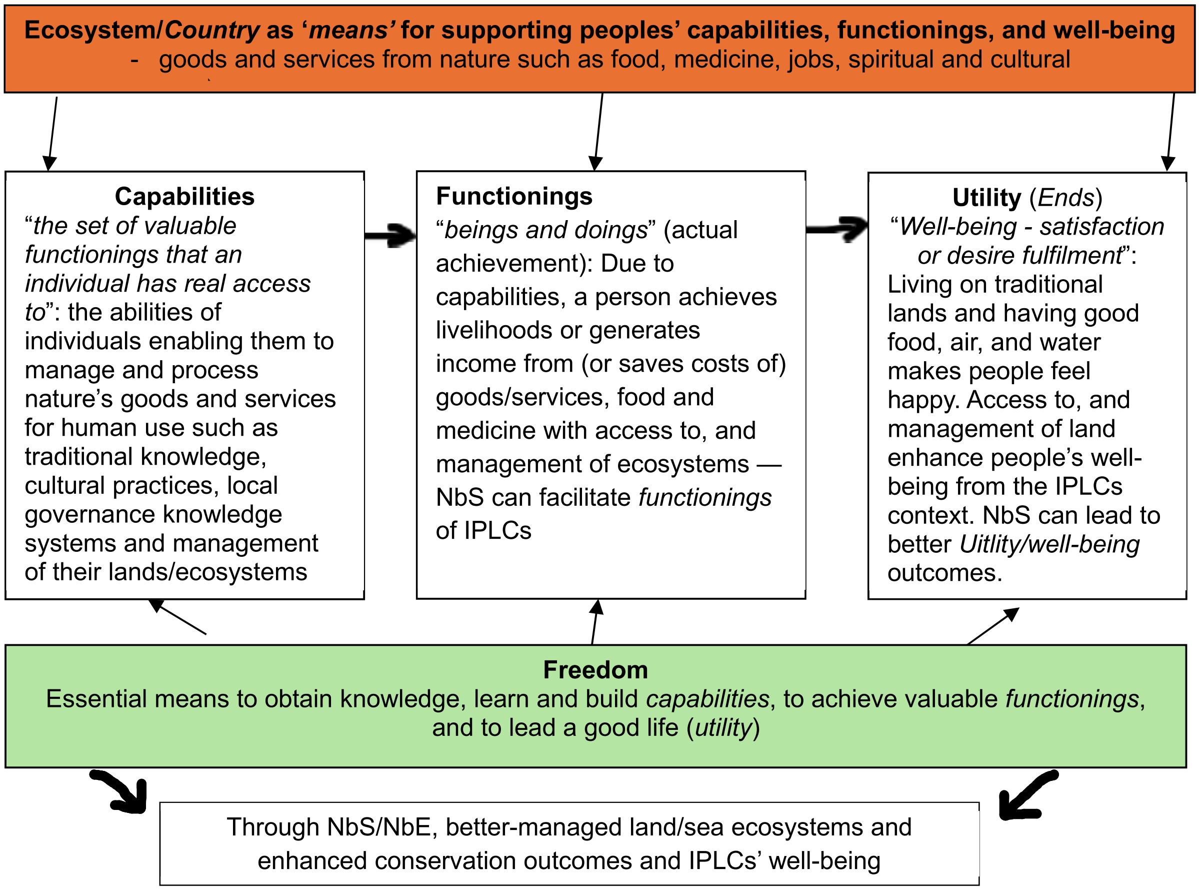

Fig. 2. The importance of considering IPLCs' capabilities for emerging NbS/NbE opportunities following Sen's Capability Approach (1999) linking Country with peoples' capabilities, functionings, and utilities.
Source: adapted from Balasubramanian & Sangha, 2023

2025).

5. Conclusion

This study has assessed ES indicators and tools that are currently commonly used to measure ecosystem conditions, but they do not extend to informing NbS/NbE opportunities. In collaboration with Indigenous groups in northern Australia, we co-developed an integrated list of both biophysical and socio-cultural indicators, measures and tools. Based on a detailed review of relevant global and Australian studies, we have proposed an integrated biocultural indicator assessment framework that can readily be applied by, and is relevant to IPLC contexts. This robust framework integrates Indigenous traditional ecological knowledges with Western/modern tools that are locally applicable for assessing Healthy *Country*/ecosystem condition, and offers advantages for emerging NbS markets involving low transactional costs, including ease of application processes for land managers. This framework can directly inform the emerging Nature Repair Markets in Australia. To our understanding, this is the first of its kind framework for integrating biophysical and cultural indicators, measures and tools to inform NbS/NbE opportunities. We contend that similar biocultural frameworks could be readily developed and adapted for application in broader IPLC contexts to realise emerging NbS/NbE opportunities.

CRediT authorship contribution statement

Kamaljit K. Sangha: Writing – review & editing, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Ronju Ahammad:** Writing – original draft, Methodology, Formal analysis. **Jeremy Russell-Smith:** Writing – review & editing, Funding acquisition, Conceptualization. **Leigh-Ann Woolley:** Resources, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2025.113230.

Data availability

we have incldued 2 appendices

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