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Integrating natural capital, life cycle assessment and industrial ecology to enhance mine closure outcomes in Australia

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Abstract

Mine closure planning across Australia is moving towards more transparent and defensible approaches for measuring long-term environmental performance, driven by clearer regulatory requirements, specific completion criteria and periodic review cycles. Biodiversity and ecosystem services remain weakly integrated into life cycle assessments (LCA). Current NCA and LCA methods capture a limited range of ecological pressures, resulting in closure planning that overlooks changes in habitat condition, and the long recovery periods typical of Australian systems. Natural capital accounting (NCAcc) methods can be applied alongside LCA when assessing environmental impacts to provide a structured way to quantify and value ecosystem services change throughout the mine life.

Nature-positive closure outcomes are defined as measurable improvements in ecosystem condition, ecosystem service provision and residual risk reduction, assessed against agreed post-mining land uses (PMLUs), completion criteria and regulatory relinquishment objectives. While ecological recovery is inherently influenced by local conditions, this study focuses on the broader challenge that conventional assessment approaches often fail to adequately represent in a decision-relevant manner: long-term recovery trajectories, ecosystem service restoration and alternative PMLU pathways. As a result, closure opportunities that reduce future liabilities, avoid additional disturbance and create enduring environmental, social or economic value may not be fully recognised within closure decision-making frameworks.

Accordingly, this paper advances the proposition that mine-closure assessment frameworks integrating LCA NCA, NCAcc and industrial ecology (IE) are better suited to contemporary Australian closure practice than conventional LCA alone. This is because they explicitly account for long-term ecological recovery trajectories, site-specific conditions and design-led asset transformation opportunities to reduce long-term liabilities.

IE strengthens closure assessments by reframing closure from a predominantly remedial obligation to a system design problem, identifying opportunities for material re-use, infrastructure repurposing and circular material flows that can reduce disturbance and improve PMLU outcomes. Importantly, these opportunities are not limited to ecological restoration and may include alternative land uses such as renewable energy developments, water storage systems, industrial precincts and other productive post-mining assets that deliver value while avoiding additional environmental disturbance and long-term liabilities.

Using Australian case studies, this paper demonstrates how integrating LCA, NCA, NCAcc and IE supports more transparent comparison of closure pathways, stronger restoration planning, reduced nature-related risk and more credible nature-positive closure outcomes aligned with regional and regulatory expectations.

Keywords: *ecosystem services, natural capital, industrial ecology, material circularity, sustainable development*

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1 Introduction

Mine closure planning in Australia has transitioned from an end-of-operational-life engineering task to a life cycle governance challenge requiring transparent, measurable and defensible demonstrations of long-term environmental performance. Contemporary closure guidance defines success as progress towards agreed post-mining land uses (PMLUs) and environmental outcomes over time. This reflects broader expectations for accountability in managing long-term environmental liabilities and demonstrating closure performance throughout the life of an asset. Therefore, mine closure is an ongoing performance management process that spans planning, operations, rehabilitation and post-closure stages. Closure outcomes are increasingly defined through traceable baselines, agreed PMLU and measurable indicators of performance. This creates a need for approaches capable of evaluating ecological and social outcomes across extended recovery periods.

Regulatory, investor and community expectations increasingly require mine closure to demonstrate value creation beyond compliance, including measurable improvements in ecosystem condition, resilience and post-mining land use outcomes. In the context of mine closure, nature-positive outcomes may be characterised as measurable improvements in ecosystem condition, function and service provision; and residual risk reduction, while supporting the agreed PMLU and reducing future environmental liabilities. Importantly, these outcomes are inherently region-specific. Arid rangelands, tropical ecosystems, wetlands, forests and coastal environments recover through fundamentally different ecological pathways. They operate on different timescales and support different ecological, cultural and economic values. Nature-positive closure therefore requires assessment approaches capable of recognising site-specific recovery trajectories while also identifying opportunities to avoid additional disturbance and create long-term value.

Life cycle assessment (LCA) and natural capital assessment (NCA) is widely used in mining to support structured, system-wide evaluation of alternative options by assessing environmental impacts, ecosystem dependencies and associated trade-offs [International Organization for Standardization (ISO) 2006a, b]. When applied effectively, its consistency, transparency and standardisation make it attractive for evaluating environmental trade-offs across alternative project designs and operational pathways. NCA can evaluate which option results in the best long-term outcome but it is not primarily designed as a long-term monitoring framework. Moreover, applying LCA and NCA to mine closure exposes significant methodological limitations. Curran et al. (2011) describe life cycle impact assessment (LCIA) as the analytical step of LCA that focuses on potential impacts and translates inventory flows into category indicators. This methodology is consistent with ISO-aligned LCIA frameworks discussed in Environmental Protection Authority and Society of Environmental Toxicology and Chemistry (SETAC) literature. LCIAs usually occur over time frames in which cause-and-effect relationships between environmental pressure and impacts can be well understood and quantified. However, LCIAs generally exclude longer-term ecological effects because they are difficult to model, which is attributed to their high uncertainty, non-linear behaviour and site-specific nature. This results in a robust understanding of near-term environmental pressures but inherently limits the ability of LCIA to represent decadal-scale ecosystem recovery as well as succession and resilience processes. Closure performance often depends on ecological processes that unfold over decades or longer, yet LCIA methods typically prioritise shorter assessment horizons, limited spatial resolution and simplified indicators of ecosystem change. Existing LCIA and NCA approaches struggle to adequately represent biodiversity, ecosystem services and long-term ecological recovery. As a result, important aspects of closure performance may not be fully considered in closure decision-making if applying the LCA and NCA approach on its own (Curran et al. 2011). Moreover, as expectations around nature-related performance and disclosure are rising, frameworks focused on ecosystem condition, ecosystem service flows and nature-related risks increasingly emphasise the need to track environmental change over time. These developments align closely with mine closure data requirements but sit largely outside traditional LCA and NCA practice.

Natural capital (NC) refers to the world's stock of natural resources – including land, water, air, soil, minerals, forests, biodiversity and ecosystems, whereas NCAcc is a consistent, repeatable framework used to quantify and track changes in ecosystem assets (stocks) and the services they provide (flows) over time to support planning, forecasting and reporting. While typically used to define disturbance impacts due to construction of a new asset, applying NCAcc logic to the closure context reframes closure performance in terms of changes in ecosystem assets, condition and service provision over time, enabling recovery to be assessed as a trajectory rather than a fixed end point.

Industrial ecology (IE) applies system thinking to optimise resource use and minimise waste across the life cycle of industrial systems. The approach identifies opportunities to repurpose materials, infrastructure and waste streams. In closure planning, this reframes the remediation phase as a design problem or opportunity rather than a rehabilitation obligation. Through infrastructure repurposing, material re-use, circular resource flows and alternative PMLUs, IE can reduce long-term liabilities, avoid disturbance and create enduring environmental, social and economic value. Together, LCA, NCA, NCAcc and IE provide a practical methodology for evaluating closure and repurposing opportunities in a manner that is time-explicit, outcome-focused and aligned with ecological realities and regulatory expectations.

In this paper, NCA is used as a decision-support assessment framework for comparing alternatives, whereas NCAcc is used as the structured accounting framework for measuring and tracking ecosystem assets and ecosystem-service flows through time. This paper advances the proposition that integrating LCA, NCA, NCAcc and IE strengthens mine closure decision-making and improves the defensibility of closure outcomes. The framework is illustrated in Figure 1 and shows how LCA, NCA, NCAcc and IE interact to support transparent comparison of closure and repurposing options by evaluating environmental trade-offs, ecosystem recovery trajectories, circular resource opportunities and long-term value creation. Integrating these complementary approaches enables evidence-based decision-making that reduces long-term liabilities, strengthens ecosystem recovery outcomes and identifies higher-value post-closure land uses. Using Australian case studies, this paper examines how this integrated framework retains the comparative strengths of LCA while addressing key limitations associated with biodiversity, ecosystem services and long-term recovery. In doing so, it supports a transition from compliance-driven closure towards value adding, asset transformation, nature-positive outcomes assessed against regional ecological realities, agreed PMLU and increasingly outcome-focused regulatory expectations. The framework enables comparison of closure pathways on their capacity to minimise impacts, enhance ecosystem condition, reduce long-term liabilities, support circular resource use and create enduring environmental, social and economic value.

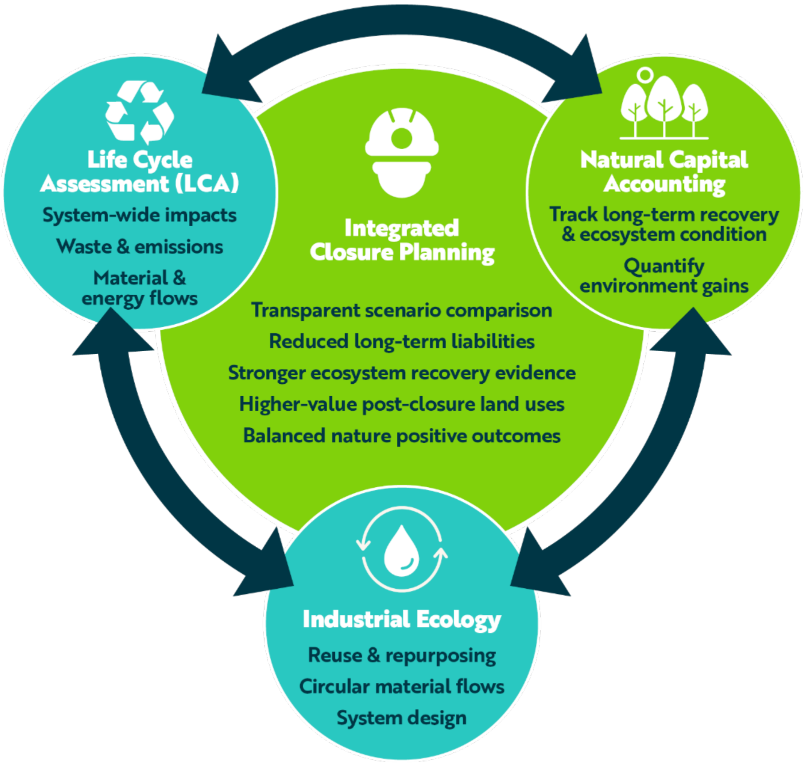

Figure 1 Conceptual framework for integrated closure planning using life cycle assessment, natural capital accounting and industrial ecology

2 Mine closure accountability in Australia

Contemporary closure governance requires demonstration of closure completion criteria encompassing environmental performance, landform stability, public safety and sustainable PMLU outcomes. The World Bank Group (2021) describes closure governance as an integrated system encompassing technical, social, environmental and financial dimensions of mine closure. Together, these dimensions provide the framework through which closure risks, liabilities, ecosystem outcomes and PMLU objectives are managed over time, linking closure planning directly to financial assurance, relinquishment pathways and long-term stewardship obligations (World Bank 2021).

Australian mine closure regulation is primarily outcome-based and life-of-asset focused in intent. Jurisdictions such as Western Australia, Queensland and New South Wales require closure planning to commence early, be updated periodically, and remain aligned with the evolving conditions of the operation through to post-closure management and relinquishment. Regulatory frameworks emphasise progressive rehabilitation, early identification of closure risks, clearly defined completion criteria and demonstrable progress towards agreed PMLUs (CRC TiME 2022; Guj & Rogerson 2024). In Western Australia, all mining proposals must include a mine closure plan that is reviewed and resubmitted at least every 3 years, with updated guidance effective from September 2025 that reinforces expectations for early and progressive rehabilitation aligned with approved closure plans and auditable evidence that closure objectives are being achieved (Department of Mines, Industry Regulation and Safety 2020; 2025). Similar requirements exist in Queensland and New South Wales, where rehabilitation objectives and completion criteria are linked to approved final land uses and subject to periodic review and performance assessment (Queensland Government 2023; NSW Resources Regulator 2021). Collectively, these frameworks require traceable baselines, end states and land-use-aligned indicators. They also require periodic reassessment and evidence of progress towards closure objectives, thereby increasing demand for assessment approaches capable of integrating long-term change, spatial variability and outcome-focused performance into closure decision-making [Cooperative Research Centre for Transformations in Mining Economies (CRC TiME 2022)].

LCA is relevant in this context because it was specifically developed to assess environmental impacts across an entire life cycle rather than at a single point in time (ISO 2006a, b). While no Australian jurisdiction prescribes LCA as a regulatory requirement for mine closure, its life cycle framing is consistent with regulatory expectations that closure performance be demonstrated across planning, operations, rehabilitation and post-closure stages rather than being treated solely as an end-of-operational-mine-life administrative exercise. Despite these strengths, important limitations remain regarding biodiversity, ecosystem services and long-term ecological recovery, which are discussed in Section 3. (Curran et al. 2011).

Regulatory requirements are increasingly aligned with broader expectations for nature-positive closure. Contemporary closure frameworks increasingly emphasise progressive rehabilitation, reduction of residual environmental risks, and PMLUs that deliver enduring ecological and social value. These expectations increasingly emphasise improvements in ecosystem condition, ecosystem service provision and long-term value creation in addition to achieving physical stability and rehabilitation objectives. The integration of LCA, NCA, NCAcc and IE provides a transparent mechanism for evaluating these outcomes by linking ecological recovery trajectories, ecosystem service provision and design-led opportunities that reduce liabilities and improve post-mining landscapes. These approaches provide a transparent basis for assessing progress towards nature-positive closure outcomes and agreed completion criteria.

Despite increasing regulatory emphasis on long-term ecological trajectories, PMLU outcomes and progressive demonstration of closure performance, conventional assessment approaches remain largely focused on static end states or isolated environmental indicators. This creates a growing mismatch between the evidence regulators seek and the information available to support closure decision-making. Together, these approaches provide a more integrated, time-explicit and outcome-focused basis for evaluating closure pathways and demonstrating progress towards completion criteria, nature-positive outcomes and relinquishment objectives.

3 Life cycle impact assessment in closure planning

LCA provides a valuable framework for comparing environmental impacts across project alternatives and operational pathways. However, mine closure decisions expose important limitations in prevailing LCIA approaches, particularly relevant where closure outcomes depend on biodiversity, ecosystem services and long-term ecological recovery processes that are difficult to represent through standardised impact indicators (Curran et al. 2011).

In LCIA methods, biodiversity is represented using simplified indicators such as species richness or potential species loss, with limited consideration of ecosystem structure, functional processes or the mechanisms that underpin recovery (Chaudhary et al. 2015; Curran et al. 2011). Ecosystem services, such as habitat provision, nutrient cycling or hydrological regulation, are rarely integrated in a meaningful way, despite their central role in defining environmental stability, restoration success and PMLU outcomes (Schaubroeck et al. 2020). Key ecological drivers relevant to closure performance, including invasive species occurrence and altered disturbance regimes, are also largely absent from mainstream LCIA practice (Verones et al. 2020).

These conceptual gaps are reinforced by spatial and temporal limitations of LCIA. LCIA methods typically prioritise time frames over which pressure-response relationships are sufficiently understood to support standardised characterisation factors. Longer-term ecological dynamics are often excluded because they involve greater uncertainty, non-linearity and site-specific feedback [United Nations Environment Programme & Society of Environmental Toxicology and Chemistry (UNEP-SETAC) 2016]. As a result, environmental impacts are commonly assessed over short- to medium-term periods and at coarse spatial scales, limiting the ability of LCIA to capture recovery trajectories, successional pathways and ecosystem resilience – processes that are fundamental to mine closure.

This limitation is particularly evident in Australian ecological contexts, where ecosystem functions critical to closure success develop over extended timescales. Habitat provision in forested ecosystems depends not only on vegetation cover but on structural attributes such as tree hollows, coarse woody debris and canopy complexity. In the South West region of Western Australia, jarrah (*Eucalyptus marginata*) and marri (*Corymbia calophylla*) forests illustrate this challenge: hollows suitable for many bird and mammal species form only after about 130 years, with some structural features requiring several centuries to develop (Gibbons & Lindenmayer 2002; Lindenmayer et al. 2012). Long-term studies demonstrate that fauna recolonisation is constrained by the availability of these slow-forming structures, resulting in non-linear and asynchronous recovery patterns despite rapid early vegetation establishment (Nichols & Grant 2007). Consequently, vegetation establishment alone may provide a poor proxy for ecosystem recovery, particularly where closure objectives depend on the return of ecological function and habitat quality.

Ecosystem services are even less integrated in mainstream LCA practice. A bibliometric review assessing more than 56,000 ecosystem services and LCA publications identified only 91 LCA studies that integrate biotic ecosystem services in a meaningful way, concluding that the 2 fields evolved with little interaction despite shared objectives (Schaubroeck et al. 2020). However, while UNEP-SETAC guidelines on land-use impact assessment explicitly identify biodiversity, ecosystem services, reversibility, regeneration time, and the spatial and temporal distribution of impacts as elements that should be explicitly considered and justified, no single LCIA method currently captures this complexity in a way that directly applies to mine closure planning (UNEP-SETAC 2016).

The challenge is compounded by the regional nature of ecological recovery. Ecosystems differ substantially in their recovery mechanisms, rates of succession and provision of ecosystem services. Standardised impact indicators applied at broad spatial scales may inadequately represent local ecological condition, recovery trajectories and long-term closure performance, particularly where climate, substrate, disturbance history and agreed PMLU objectives vary substantially between regions. This creates a mismatch between the simplified impact categories typically used in LCIA and the site-specific evidence required to demonstrate progress towards closure outcomes.

Mine closure is inherently about long-term recovery trajectories, yet current LCIA methods do not adequately capture this complexity. Existing approaches remain limited in their ability to evaluate biodiversity, ecosystem service provision and ecosystem recovery over extended timescales that define closure success. These limitations are amplified in Australia, where ecological recovery can span decades to centuries and where closure performance is assessed through progressive achievements of outcomes rather than a single end point condition. Long-term restoration studies show that while some species return quickly, others depend on these slow-forming habitat structures, reinforcing the need for trajectory-based assessment. These limitations underscore the need for complementary approaches that evaluate changes in ecosystem condition, function and value over time while capturing the ecological recovery trajectories that define successful mine closure outcomes (Department of Climate Change, Energy, the Environment and Water 2025).

4 Natural capital as a decision framework

NCAcc addresses several limitations of conventional LCIA by explicitly evaluating changes in ecosystem assets, ecosystem condition and ecosystem service provision over time. CRC TiME Project 2.7 distinguishes NC from NCA and NCAcc. NC is the stock of ecosystem assets. NCA is a decision-support process used to assess ecosystem dependencies, impacts, risks and opportunities. NCAcc is a structured framework for measuring and tracking changes in ecosystem extent, condition and ecosystem-service flows over time. (CRC TiME 2022). Whereas LCIA primarily quantifies potential environmental impacts associated with activities and resource flows, NCAcc focuses on measuring and tracking the condition, extent and value of ecological assets and the services they provide. This enables closure performance to be assessed as a recovery trajectory rather than a fixed end-state condition, providing a stronger basis for evaluating long-term ecosystem recovery and progress towards agreed PMLU outcomes.

Frameworks such as the System of Environmental-Economic Accounting – Ecosystem Accounting (SEEA EA) provide consistent and repeatable approaches for quantifying changes in ecosystem stocks and service flows, supporting planning, forecasting and reporting throughout the life of an asset (United Nations 2021). Within mine closure, these approaches provide a mechanism for measuring changes in ecosystem extent, condition and functionality across pre-mining, operational, rehabilitation and post-closure phases. As a result, NCAcc can help bridge the gap between conventional impact assessment and the long-term ecological outcomes required to demonstrate closure success.

The Natural Capital Protocol similarly positions NCAs as decision-support tools that enable comparison of alternative closure pathways and their effects on ecosystem assets and service provision (Natural Capital Coalition 2016). By making changes in ecosystem assets and service provision explicit, the protocol helps transparently evaluate trade-offs. It illustrates how alternative closure pathways may reduce impacts, manage risks or contribute towards agreed PMLU objectives. Importantly, these approaches inform decision-making rather than prescribe acceptable outcomes; allowing closure objectives to remain aligned with regulatory requirements, stakeholder expectations and site-specific contexts.

Practical applications within the mining sector demonstrate the increasing maturity of these approaches. Applications by organisations such as Alcoa and BHP show how ecosystem condition, stocks and service flows can be tracked over time using NCAcc to assess rehabilitation performance and support environmental reporting (BHP 2023; O'Grady et al. 2024). These approaches provide a structured means of distinguishing between land that has achieved physical stability and ecosystems that are demonstrating functional recovery; an important distinction in outcome-based closure planning.

At the same time, recent literature highlights important limitations in the application of NC approaches. Normyle et al. (2025) highlight a critical gap in how NC and Disclosures frameworks such as the Task Force on Nature-related Financial Disclosures, inform decision-making. The authors argue that many contemporary NC frameworks continue to under-represent First Nations' values, knowledge systems and relationships to the land. In a mine closure context, this creates risk that technically successful rehabilitation outcomes may not align with culturally or socially acceptable PMLUs. Addressing this limitation requires deliberate engagement, co-design and recognition of First Nations' knowledge systems throughout the closure planning and assessment process.

Despite these challenges, NCAcc provides an important complement to LCIA and NCA because it enables ecological change, ecosystem service provision and recovery trajectories to be evaluated through time rather than inferred from static impact indicators. This capability aligns closely with contemporary mine closure requirements, which emphasise demonstratable progress towards agreed outcomes, ecosystem restoration and nature-positive performance. By translating ecological change into structured, decision-grade information, NCAcc assists to clearly communicate ecosystem recovery trajectories, risks and residual liabilities to regulators and stakeholders.

5 Industrial ecology

While LCIA improves understanding of environmental impacts and NCAcc strengthens evaluation of ecosystem recovery trajectories, neither framework explicitly addresses how closure systems can be redesigned to reduce liabilities and create long-term value. IE addresses this challenge by applying systems thinking to the configuration, re-use and transformation of materials, infrastructure and landforms throughout the closure process. As articulated by the International Society for Industrial Ecology, LCA is one of several core methods used within IE, alongside tools such as material flow analysis, substance flow analysis and industrial symbiosis. In this broader framing, LCA and NCA provides quantitative, system-wide comparison of environmental pressures, while IE situates those analyses within a design-oriented understanding of coupled industrial and natural systems. IE extends beyond impact assessment by considering how materials, infrastructure and landforms can be reconfigured to improve long-term environmental, social and economic outcomes while reducing residual liabilities (ICMM 2025; Chugh et al. 2023).

From a regulatory perspective, mine closure represents a critical transition point at which operational assets, such as waste rock, tailings, voids, water management systems and infrastructure, become long-term liabilities or post-mining resources. Regulators require proponents to demonstrate that decommissioning and closure will result in safe, stable and non-polluting outcomes (IGF 2023; ICMM 2025). IE supports this requirement by treating closure as a system-configuration problem; enabling assessment of how alternative closure pathways influence long-term material stability, contaminant behaviour, maintenance burden and land-use constraints.

IE approaches, including material flow analysis, substance flow analysis, industrial symbiosis and system-level scenario assessment, provide additional structure for evaluating alternative closure configurations. Rather than focusing solely on compliance actions or short-term capital costs, these approaches help compare closure pathways based on long-term environmental performance, resource efficiency and liability profile – attributes directly relevant to outcome-based closure regulation and progressive risk reduction (Oliveros-Sepúlveda et al. 2025; Pavloudakis et al. 2023).

Governments and regulators have identified unresolved material legacies, infrastructure suitability and land-use incompatibility as key barriers (IGF 2023). By reframing closure assets as potential secondary resources, through re-use, repurposing or integration into post-mining systems, IE provides a defensible basis for reducing long-term liabilities while remaining consistent with regulatory safety and environmental constraints. For example, repurposing pit voids for pumped hydroelectric energy storage or water storage can transform a long-term physical and safety liability into productive infrastructure; reducing closure obligations and creating ongoing value. This example demonstrates how circularity and repurposing can materially reduce residual risks, minimise long-term liabilities and improve the likelihood of achieving stable, regulator-accepted closure outcomes.

Within the integrated framework proposed in this paper, LCA and NCA evaluates environmental impacts, NCAcc tracks the ecosystem condition and service provision, and IE informs the design of closure systems capable of reducing liabilities while creating long-term value. Together, these complementary approaches support more transparent, defensible and outcome-focused closure decision-making, enabling comparison of closure pathways on their capacity to minimise impacts, support ecosystem recovery, reduce liabilities, and deliver enduring environmental, social and economic benefits aligned with agreed PMLUs and closure objectives.

6 Integrating life cycle assessment, natural capital and industrial ecology

The practical challenge is integrating LCA, NCA, NCAcc, and IE within existing mine closure planning processes while retaining the strengths of each approach. The integrated framework proposed in this paper combines the comparative strengths of LCA, NCA and NCAcc with trajectory-based ecosystem assessment and design-led closure planning to better reflect the ecological, regulatory and operational realities of mine closure.

Using Australian case studies, the framework demonstrates how alternative closure strategies can be systematically compared based on environmental impacts, ecosystem recovery trajectories, circular resource opportunities and long-term value creation. This integrated approach can support more transparent, defensible and value-adding closure decisions. In doing so, it provides a practical pathway for aligning closure assessment methods with evolving regulatory expectations and the ecological realities of Australian systems, supporting a broader shift from compliance-driven closure towards measurable, nature-positive outcomes.

Figure 2 presents a practical framework for integrating LCA, NCAcc and IE within existing mine closure planning processes. The framework illustrates how closure objectives, alternative PMLUs and progressive rehabilitation activities can be evaluated through integrated scenario assessment and subsequently monitored against completion criteria and relinquishment requirements.

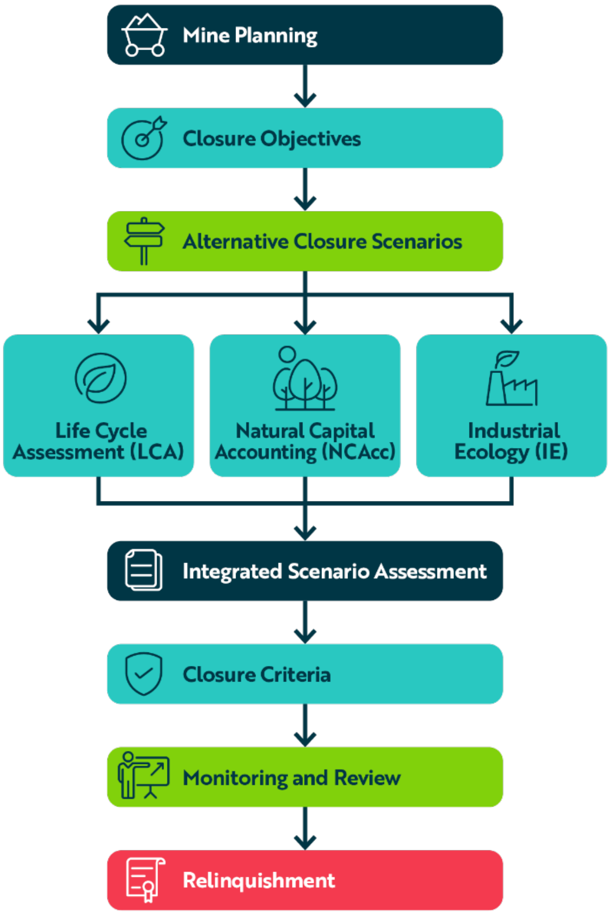

Figure 2 Practical framework for integrating life cycle assessment, natural capital assessment and accounting, and industrial ecology within mine closure planning and decision-making

Importantly, the framework is not intended to replace mine closure planning processes. Rather, it provides an additional layer of decision support that links environmental impacts, ecological recovery trajectories and asset transformation opportunities within a consistent assessment structure.

A practical approach rests on several core design shifts. The life cycle inventory must expand beyond traditional metrics to include closure-specific activities such as landform reconstruction, ecosystem management and long-term monitoring. LCIA methods should be spatially and temporally robust for land use, then supplemented with local ecological models where needed. These outputs are then linked to NC accounts, tracking ecosystems as evolving assets with changing condition and service flows, and supporting trajectory-based assessment aligned with, and potentially informing, closure criteria.

Finally, integrating IE introduces design levers to reduce closure liabilities through circularity, material re-use and improved waste pathways. This aligns with broader policy directions and tailings management standards (Australian Government 2023; ICMM 2020; Lèbre et al. 2017), managing risks through design rather than deferring them. Together these elements enable an integrated closure scenarios framework, directly addressing gaps in biodiversity and ecosystem service assessment, whereby:

- LCA and NCA provides system-wide, consistent comparability
- NC tracks the range and quality of ecosystem services
- IE reduces long-term impacts and accounts for circular design (Graedel & Allenby 2010).

Key design principles include:

- closure-inclusive system boundaries
- expanded inventories capturing ecological interventions
- spatially explicit modelling
- long-term ecosystem tracking
- circular material flows.

In practice, the framework could be integrated into existing mine closure planning processes by establishing NC baselines during mine planning, incorporating closure activities and ecological interventions into life cycle inventories, evaluating alternative PMLUs through scenario analysis, and using NCAcc and IE metrics to periodically review progress against completion criteria, closure objectives and relinquishment requirements.

7 Application of the integrated frameworks in Australian contexts

Australia’s mine closure challenge is highly context-specific, making regionalisation essential rather than optional. Land use LCIA guidance already highlights the need for biogeographical differentiation, clear reference conditions and transparent modelling of regeneration time frames (CSIRO 2023). The following case studies illustrate how integrated LCA, NCA, NCAcc and IE approaches can support closure decisions across a range of Australian environmental, regulatory and PMLU contexts. Together they demonstrate the flexibility of the framework when applied to infrastructure repurposing, renewable energy redevelopment, ecosystem restoration and alternative PMLU evaluation.

This aligns directly with Australian closure practice, where completion criteria are tailored to site-specific environmental, social, cultural and economic values, the intended PMLU, and the physical and ecological characteristics of the receiving landscape. The examples discussed illustrate why generic assumptions about ecological recovery are often inappropriate in Australian closure contexts. Recovery trajectories vary substantially between ecosystems. In arid regions such as the Pilbara in Western Australia, restoration is constrained by soil reconstruction challenges and difficulties in re-establishing keystone species such as spinifex (Erickson et al. 2016). In tropical and wetland-adjacent systems, closure involves long-term staged rehabilitation and ongoing management of weeds, erosion and ecosystem stability. These contrasting recovery pathways demonstrate that closure success is inherently context-dependent and reinforce the need for site-specific, time-explicit assessment approaches rather than nationally uniform assumptions regarding ecosystem recovery. As a result, national 'one size' LCIA approaches risk missing the key factors that matter for closure success, including invasive species, habitat condition and functional ecosystem recovery. A practical way forward is to develop targeted case studies across contrasting Australian contexts, such as Pilbara iron ore, jarrah forest bauxite, coal basins and tropical systems, to demonstrate how integrated LCA, NC and IE approaches can improve closure decision-making and outcome defensibility.

7.1 Case study: Kidston mine, Queensland

The Kidston gold mine operated from 1984 to 2001, about 280 km northwest of Cairns in Far North Queensland. After gold processing ceased, Genex Power acquired the site and progressively redeveloped it as the Kidston Clean Energy Hub. Stage 1 of the project included the installation and operation of a 50-MW solar photovoltaic facility (commissioned in 2017) constructed on the rehabilitated tailings storage facility by directly using existing mined land, access roads, internal power distribution and grid connection assets while avoiding additional land disturbance on surrounding pastoral landscapes (ARENA 2021; Genex Power Limited 2022a, 2022b). In Stage 2 the Kidston Pumped Storage Hydro Project was constructed, which repurposed the 2 largest open pit voids as upper and lower reservoirs for a 250-MW pumped hydroelectric storage facility, with co-funding secured from the Australian Renewable Energy Agency and the Queensland Government (ARENA 2021; Queensland Coordinator-General 2019). The closed-loop design avoids impacts to natural river systems, eliminating the need for river-related approvals, minimises water top-up requirements and confines infrastructure largely within the existing mining lease footprint; a key consideration identified through the project's impact assessment and approvals process (Queensland Coordinator-General 2019).

From an integrated assessment perspective, Kidston primarily demonstrates the IE component of the framework. IE is embedded in its re-use of pit void geometry, legacy landforms and transmission infrastructure, avoiding the additional material use and land clearing associated with a greenfield pumped hydro development. NCAcc can track the shift from a degraded post-mining landscape towards a stabilised state and productive land use, quantify avoided ecosystem service losses relative to unconstrained or deferred closure, and help measure progressive ecosystem condition recovery across rehabilitated waste rock dumps, tailings facilities and surrounding land uses. Long-term rehabilitation performance at Kidston, including effective waste rock encapsulation, store-and-release covers and successful revegetation sustained over more than 2 decades, provides an empirical basis for treating ecosystems as evolving assets rather than static closure end states (Williams et al. 2022).

LCA can then be applied to compare the life cycle energy, emissions and land-use footprints of the integrated clean energy hub against conventional rehabilitation-only closure pathways. This enables comparison of a productive PMLU against rehabilitation-only closure strategies, demonstrating how design-led asset transformation can reduce long-term liabilities while creating ongoing environmental and economic value (ARENA 2021; Queensland Coordinator-General 2019).

7.2 Case study: Mt Rawdon mine, Queensland

The Mt Rawdon open pit gold mine, operated by Evolution Mining near Mount Perry in South East Queensland, provides a contrasting example of integrated closure pathway assessment. Standard closure planning for Mt Rawdon involves progressively rehabilitating the site to local bushland and storing water within the pit void, consistent with Evolution Mining's statutory rehabilitation obligations under Queensland's Progressive Rehabilitation and Closure Plan framework (Evolution Mining Limited 2023). A higher-value PMLU is proposed: the Mt Rawdon Pumped Hydroelectric Energy Storage (PHES) Project, which would use the existing pit void as a lower reservoir for a pumped hydro facility, with the potential to deliver renewable energy into the Queensland grid (Frontier Energy Limited 2023).

Unlike Kidston, which demonstrates an implemented repurposing outcome, Mt Rawdon highlights the importance of evaluating alternative closure pathways before irreversible rehabilitation decisions are made. NCAcc can quantify ecosystem condition and service trajectories under both scenarios, while LCA and IE support the comparison of environmental impacts, resource use and infrastructure re-use opportunities. IE analysis can evaluate the potential for re-using material and infrastructure, and identify circular design options that minimise new disturbance. LCA and NCA can capture life cycle emissions and land-use impacts across scenarios, making trade-offs across impact categories visible and defensible. Taken together, integrated assessment enables both the operator and the regulator to make ecological, economic and social closure pathway decisions based on clearly evidenced value creation rather than least-cost compliance with the minimum of statutory obligations.

7.3 Case study: solar repurposing of mined land

The redevelopment of mined land for utility-scale solar generation demonstrates that integrated LCA, NCA, NCAcc and IE frameworks are applicable beyond pumped hydro systems. The 50-MW Kidston Solar Farm utilised rehabilitated tailings storage facilities and existing transmission infrastructure, providing an example of how renewable energy redevelopment can be incorporated into closure planning through productive re-use of previously disturbed land.

From an IE perspective, the project demonstrates infrastructure repurposing and circular land use by converting previously disturbed land into productive renewable energy assets. NCA can quantify avoided ecosystem disturbance and NCAcc monitor ecosystem condition trajectories associated with rehabilitated landforms. LCA can compare life cycle emissions, land use impacts and material requirements against equivalent greenfield solar developments. This example demonstrates that integrated closure frameworks can support a wide range of PMLUs and are not limited to hydroelectric redevelopment. More broadly, it illustrates how IE principles can create value through alternative land use pathways while reducing pressure for additional disturbance elsewhere in the landscape.

7.4 Case study: Ranger uranium mine, Northern Territory

The closure and rehabilitation of Ranger uranium mine provides a contrasting example of integrated closure assessment where value creation is derived primarily through ecological restoration rather than infrastructure repurposing or renewable energy redevelopment. Closure objectives focus on returning the site to an ecosystem that can be incorporated into the surrounding landscape of Kakadu National Park and meet the expectations of traditional owners and regulators (DCCEEW 2025).

In this context, NCAcc is particularly valuable because ecosystem recovery occurs over extended timescales and involves changes in vegetation structure, biodiversity, hydrological processes and cultural ecosystem services (DCCEEW 2025). IE contributes through optimisation of material movement, waste management and landform design rather than through redevelopment of mining assets. LCA and NCA can support comparison of rehabilitation alternatives, material requirements and long-term environmental trade-offs associated with different closure designs.

This case demonstrates that the integrated framework is equally applicable to closure pathways focused on ecological restoration and relinquishment, thereby extending its relevance beyond renewable energy repurposing and illustrating its broader utility across Australian mine closure contexts. Together these case studies demonstrate that the integrated framework is applicable across a diverse range of closure pathways, including asset repurposing, renewable energy redevelopment, alternative PMLU assessment and ecological restoration. Importantly, the framework does not assume that a single closure pathway will always deliver superior outcomes. Rather, its value lies in providing a transparent basis for comparing alternative closure scenarios and identifying those most likely to reduce liabilities, support ecosystem recovery, and create long-term environmental, social and economic value.

8 Discussion

The case studies demonstrate that closure outcomes are strongly influenced by how assessment boundaries are defined. Conventional approaches tend to focus on short-term rehabilitation performance and compliance requirements, whereas the integrated framework expands both spatial and temporal boundaries to include ecosystem recovery trajectories, ecosystem service provision and opportunities for asset transformation. While LCA and NCA provides consistency and comparability, its treatment of biodiversity, ecosystem services and long-term recovery is too simplified for closure contexts. This creates a structural gap between reported outcomes and actual ecological performance, particularly where recovery processes extend over decades or longer.

At Kidston, a NCAcc lens adds value by reframing closure success beyond physical stability or compliance with rehabilitation criteria towards the evolution of ecosystem assets and service provision over time. NCAcc enables the avoided loss of ecosystem services associated with deferred or unconstrained closure to be made explicit, while supporting monitoring of ecosystem condition across rehabilitated waste rock dumps, tailings facilities and adjacent land uses as the site transitions to a stabilised, productive post-mining system. This complements LCA and NCA by explaining why repurposing pit voids and existing infrastructure alters environmental outcomes, not only through reduced land disturbance and embodied impacts but by changing the long-term ecological trajectory of the site.

The Mt Rawdon example highlights a different but equally important contribution. Here, NCAcc enables comparison of alternative future ecosystem trajectories under a conventional rehabilitation pathway versus redevelopment as a pumped hydro energy storage facility. Rather than treating rehabilitation as a single end point, NCAcc metrics allow for evaluation of how ecosystem condition, habitat function and service provision may differ between scenarios across extended time horizons. Importantly, the framework does not assume that asset repurposing or redevelopment pathways will always deliver superior closure outcomes. Rather, its value lies in making trade-offs explicit by enabling environmental, ecological, social and economic consequences of alternative closure pathways to be compared using a common decision framework. This supports more transparent decision-making before taking irreversible rehabilitation action, ensuring PMLU choices are informed by their long-term implications for ecological function as well as energy system value.

The Kidston Solar Farm and Ranger uranium mine case studies further demonstrate the breadth of the application of the integrated framework. The Kidston Solar Farm illustrates how previously disturbed mine land can be repurposed for utility-scale renewable energy generation while avoiding additional land clearing, reducing embodied impacts and extending the productive use of existing infrastructure. In this context, IE and NCAcc work together to demonstrate how circular land use and ecosystem recovery can occur simultaneously.

By contrast, Ranger represents a fundamentally different closure objective in which value creation is derived primarily through ecological restoration and relinquishment rather than infrastructure repurposing. Closure success at Ranger uranium mine depends upon long-term ecosystem recovery, cultural values, hydrological stability and progressive demonstration that rehabilitation outcomes are converging towards the surrounding Kakadu landscape. The case therefore highlights the importance of trajectory-based assessment and reinforces the need for NCAcc approaches that can explicitly account for long-term ecological processes, nature-related risks and culturally significant ecosystem services.

The findings also have implications for closure governance and performance assessment. Existing completion criteria are frequently focused on physical stability, rehabilitation establishment and risk reduction. The integrated framework demonstrates how ecosystem condition, ecosystem service provision and recovery trajectories can be incorporated into performance measurement, potentially strengthening alignment between regulatory objectives and long-term environmental outcomes.

The case studies demonstrate that integrated LCA, NCA, NCAcc and IE frameworks are sufficiently flexible to support fundamentally different closure pathways, including renewable energy redevelopment, infrastructure repurposing, circular land use and ecological restoration. This flexibility is important because contemporary closure practice increasingly requires proponents to justify closure pathways against a broader range of environmental, social, economic and regulatory objectives than conventional rehabilitation-focused approaches alone. This broader applicability strengthens the argument that integrated assessment frameworks are more closely aligned with contemporary Australian closure practice than conventional LCA alone.

Across the case studies, NCAcc does not replace LCA or NCA but adds decision relevance by translating ecological change into trajectory-based information aligned with regulatory expectations for progressive closure performance. IE further strengthens this integration by shaping closure pathways through design – re-using voids, landforms and infrastructure to reduce disturbance, limit material inputs and avoid future liabilities. Together, these approaches show that closure decisions can be optimised through informed design and sequencing rather than minimised through least-cost rehabilitation alone.

Collectively, the case studies reinforce the 4 central propositions advanced in this paper. First, closure performance is inherently trajectory-based and therefore requires assessment approaches capable of representing long-term ecological recovery. Second, closure outcomes are highly dependent on site-specific ecological conditions and recovery pathways, meaning generic assumptions are often inadequate for decision-making. Third, integrated assessment provides a more transparent means of identifying and managing nature-related risks and residual liabilities over extended time horizons. Fourth, IE introduces design-led opportunities for repurposing infrastructure, optimising material flows and creating value while reducing long-term closure obligations.

A key implication is that closure assessment must expand both system boundaries and time horizons. Closure and post-closure stages need to be treated as central components of assessment, with spatial resolution sufficient to reflect regional ecological processes and recovery constraints. When NCAcc is used alongside LCA NCA and IE, closure pathways can be compared not only on near-term impacts but on their capacity to deliver durable ecological function, reduced residual risk and defensible long-term outcomes.

Importantly, nature-positive outcomes should not be interpreted solely as revegetation success or regulatory compliance. Across the case studies, nature-positive outcomes are achieved through measurable improvements in ecosystem condition, ecosystem service provision and residual risk reduction, consistent with the definition adopted in this paper. The integrated framework provides a transparent basis for evaluating these attributes and aligning closure performance with both regional ecological realities and increasingly outcome-based regulatory expectations.

Overall, combining LCA, NCA, NCAcc and IE enables more transparent and defensible closure decisions. These findings reinforce the central proposition of this paper that integrated assessment frameworks are better suited to Australian closure contexts because they explicitly recognise long-term recovery trajectories, regional ecological variability and design-led opportunities to create nature-positive outcomes. The integrated framework allows comparison of alternative pathways based on ecological, economic and life cycle outcomes, supporting a shift from compliance-driven closure to value creation. While challenges remain in data, methodology and integration, this approach provides a clear pathway towards more robust and nature-positive closure frameworks.

9 Conclusion

Mine closure in Australia is shifting towards a more rigorous, evidence-based discipline, driven by tighter regulatory frameworks and increasing expectations around long-term environmental performance. This paper shows that while LCA remains a valuable tool for system-wide comparison, on its own it is insufficient to support credible closure outcomes. Its limitations in representing biodiversity, ecosystem services and long-term ecological recovery mean critical aspects of closure performance are simplified or overlooked.

Integrating NCAcc addresses this gap by bringing ecological condition and ecosystem service flows into the decision-making framework. It allows closure to be assessed as a trajectory, aligning more closely with how recovery occurs in practice and how regulators increasingly define success. IE further strengthens the framework by introducing design-led solutions that reduce closure liabilities and create alternative land use value.

The case studies demonstrate that when these approaches are combined, closure can move beyond compliance and deliver measurable ecological, economic and system-wide benefits across a range of post-mining contexts. The Kidston examples show how infrastructure repurposing and renewable energy redevelopment can reduce disturbance and create higher-value land uses. Mt Rawdon gold mine illustrates the importance of evaluating alternative closure pathways before irreversible rehabilitation decisions are taken, allowing ecological and energy system values to be compared transparently. In contrast, Ranger uranium mine demonstrates that integrated assessment frameworks are equally relevant where the principal objective is ecological restoration and relinquishment. Collectively, these examples reinforce the need to expand LCA and NCA system boundaries, acknowledge industrial ecology, extend time horizons and incorporate spatially explicit data that reflect real-world ecological conditions and diverse closure objectives. The key conclusion is that improving mine closure outcomes is not about replacing existing tools but integrating them in a way that recognises ecological recovery as a long-term, location-specific and value-dependent process. Without this shift, closure frameworks risk systematically undervaluing long-term environmental performance and missing opportunities for higher-value post-mining land uses.

The findings reinforce the central argument advanced in the abstract: integrated assessment frameworks that combine LCA, NCA, NCAcc and IE are better suited to contemporary Australian closure practice because they explicitly account for long-term recovery trajectories, regional ecological variability, nature-related risks and design opportunities that can reduce liabilities and create higher-value post-mining outcomes. Importantly, the case studies demonstrate that these frameworks are applicable across a spectrum of closure contexts ranging from renewable energy redevelopment and circular infrastructure re-use to ecological restoration and relinquishment.

Future work should focus on developing regionalised datasets, refining methods for integrating ecosystem services into life cycle impact assessment and building practical case studies across different Australian contexts. This will be critical to operationalising the integrated framework and applying it consistently across projects, supporting both regulatory compliance, economic development and broader nature-positive outcomes.

Use of artificial intelligence disclosure statement

In preparing this paper the author used Microsoft 365 Copilot-GPT-5 chat model to help draft, structure and refine text. The author has reviewed the content and edited it where required, and takes full responsibility for said content.

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