# Resilience and Riverine Landscapes

Edited by Martin Thoms, and Ian Fuller

ELSEVIER

# RESILIENCE AND RIVERINE LANDSCAPES

This page intentionally left blank

# RESILIENCE AND RIVERINE LANDSCAPES

*Edited by*

MARTIN THOMS
*Riverine Landscapes Research Laboratory, Department of Geography, University of New England, Armidale, NSW, Australia*

IAN FULLER
*School of Agriculture & Environment, Massey University, Palmerston North, New Zealand*

ELSEVIER

Elsevier
Radarweg 29, PO Box 211, 1000 AE Amsterdam, Netherlands
The Boulevard, Langford Lane, Kidlington, Oxford OX5 1GB, United Kingdom
50 Hampshire Street, 5th Floor, Cambridge, MA 02139, United States



ISBN: 978-0-323-91716-2

For information on all Elsevier publications visit our website at https://www.elsevier.com/books-and-journals

*Publisher:* Candice Janco
*Acquisitions Editor:* Maria Elekidou
*Editorial Project Manager:* Sara Valentino
*Production Project Manager:* Paul Prasad Chandramohan
*Cover Designer:* Vicky Pearson Esser

Typeset by TNQ Technologies

CHAPTER

# 28

# Applying resilience thinking to rehabilitating a novel social–ecological system: A case study from the lower Ok Tedi, Papua New Guinea

*Todd R. Caplan*[1], *Bega Inaho*[2], *Markson Yarrao*[2], *Jesse Pile*[2], *Mike Milczarek*[3] *and Chad McKenna*[1]

[1]GeoSystems Analysis, Inc., Albuquerque, NM, United States; [2]Environment Department, Ok Tedi Mining Limited, Tabubil, WP, Papua New Guinea; [3]GeoSystems Analysis, Inc., Tucson, AZ, United States

OUTLINE



*Resilience and Riverine Landscapes*
https://doi.org/10.1016/B978-0-323-91716-2.00024-8

## Introduction

Subsistence communities living along the Ok Tedi in the Western Province of Papua New Guinea (PNG) have relied on the biologically rich floodplain forest and river ecosystem for food, medicines, building materials and a myriad of ecosystem services for thousands of years. 'Ok' means river in the language of the local Yongon people of Western Province, PNG. Since the mid-1980s, the Ok Tedi Mining Limited (OTML) copper and gold mine has discharged waste rocks and tailings into the headwater tributaries of the Ok Tedi, leading to excessive channel aggradation and changes in the inundation of the lowland floodplain forests along several hundred kilometers of the lower Ok Tedi and middle Fly River. To mitigate these impacts, in 1998, OTML began implementing a series of restoration activities near the lower Ok Tedi village of Bige. The aim was to reduce ecological and cultural impacts associated with excessive sedimentation, flooding and forest dieback by continuously dredging mine-derived sand from the aggraded Ok Tedi river channel and depositing the sand into large stockpiles on the east and west banks of the river. Stabilising the stockpiles with vegetation is essential for preventing erosion and exposure of underlying sulfide-rich mine waste sediments. However, the dredged sand stockpiles are physically, geochemically and biologically different from the surrounding soil substrates and represent significant challenges to revegetation. Hence, by working to alleviate one social—ecological issue, an entirely new (novel) social—ecological system was created.

Resilience refers to the capacity of a system to absorb and adapt to disturbance and reorganise such that it retains essentially the same function, structure and feedbacks (Chapter 1; Holling, 1973; Walker and Salt, 2006). Resilience thinking strives to apply this construct to resource management and landscape rehabilitation by integrating science, management and policy to embrace uncertainty, manage risk and adapt in a rapidly changing and unpredictable world (Curtin and Parker, 2014). At its core, it acknowledges that recurring problems in natural resource use and management stem from the lack of recognition that ecosystems and the social systems that use and depend on them are intimately interwoven (Chapter 1; Folke et al., 2010).

This chapter highlights three ways resilience thinking has been and continues to be applied to the rehabilitation and afforestation of dredged sand stockpiles along the Ok Tedi. The first centres on acknowledgement that the rehabilitated area is part of a complex social—ecological system (Berkes and Folke, 1998) in which indigenous communities have been living for thousands of years. Accordingly, achieving resilience requires the created forest be valued by the local people and their traditional knowledge be integrated into afforestation practices. The second involves embracing that resilience, biodiversity and sustainability are inextricably linked (Folke et al., 2004; Oliver et al., 2015; Chapter 14), and that creating a resilient forest ecosystem on the stockpiles requires rehabilitation techniques centred on converting this biologically inert substrate to a functional soil capable of supporting diverse forest species with functional redundancy. The third centres on recognising that the dredged sand stockpiles comprise a novel ecosystem and that succession of newly established vegetation may follow a range of potential structural and compositional pathways. To achieve resilience in the face of future disturbances, both natural and anthropogenic, the emphasis of the programme is on creating conditions that facilitate the development and upward trajectory of key ecological functions rather than striving to match the structure and composition of the surrounding rainforest. Monitoring response trajectories inform adaptive management aimed at expediting development of functional processes.

In the following sections, we introduce the lower Ok Tedi as a complex social–ecological system and explain how the OTML mine impacted both the riverine environment and the local communities that rely upon its ecosystem services to support their livelihood and culture. We then review how OTML integrated newly emerging concepts of resilience and novel ecosystems early in the stockpile rehabilitation planning process and how local communities play an integral role in ensuring culturally important forest species are an essential component of the rehabilitation program. We describe how ecosystem functional trajectories are being measured and used to evaluate rehabilitation success and how monitoring results are being used to guide adaptive management actions. We conclude by summarising how resilience thinking and the rehabilitation framework employed at lower Ok Tedi may be transferable to other novel ecosystems around the world.

## The complex social-ecological system of Ok Tedi

Applying resilience thinking to management of natural resources inherently involves an acceptance that humans are embedded in the biosphere and interact with it in multiple ways to shape ecosystems at local to global scales, that is, ‘a social–ecological system’ (Berkes and Folke, 1998). The complex relationship that exists between the subsistence communities of the lower Ok Tedi and the natural world is a quintessential example of a social–ecological system. It is also a relationship that has changed over time (Fig. 28.1) due to multiple political influences and mine-related impacts to the ecosystem services provided to communities by the Ok Tedi river system. To appreciate this complexity and understand the approach to rehabilitation undertaken by OTML managers, it is important to provide some background on aspects of PNG society and culture.

Papua New Guinea is an independent and democratic nation that comprises the eastern half of the island of New Guinea along with several hundred smaller islands off the eastern coast (Fig. 28.2). The western half of the island (formerly Irian Jaya but renamed ‘Papua’ in 2000) is controlled by the Indonesian government. Indigenous people have occupied the island of New Guinea for about 50,000 years (Griffin et al., 1979). PNG spans 462,840 $km^2$ of which 61% (282,520 $km^2$) is covered by tropical rainforest (Shearman et al., 2009), the world’s third largest after the Amazon and Congo rainforests, respectively. The landscape is topographically rugged with a vast range of forested mountains and valleys running through the middle of the mainland (the Highlands). The overall landscape includes an extraordinary range of terrestrial, fresh water and marine environments that are believed to harbour more than 5% of the world’s biological diversity (Sekhran and Miller, 1996).

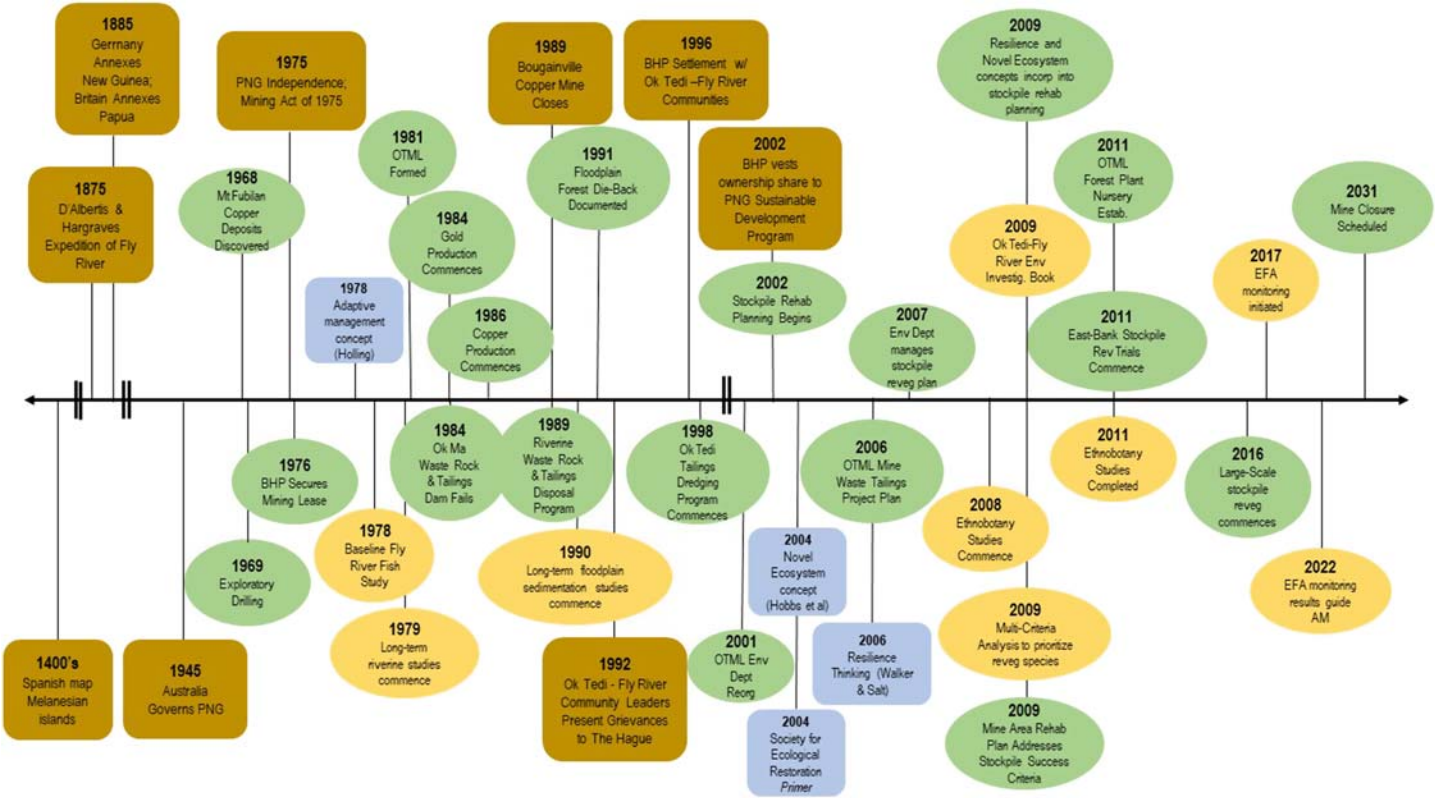


FIGURE 28.1 Timeline of notable historical–political events (brown), mine development activities (green), mine-related ecological studies (yellow) and influential ecological constructs (blue).

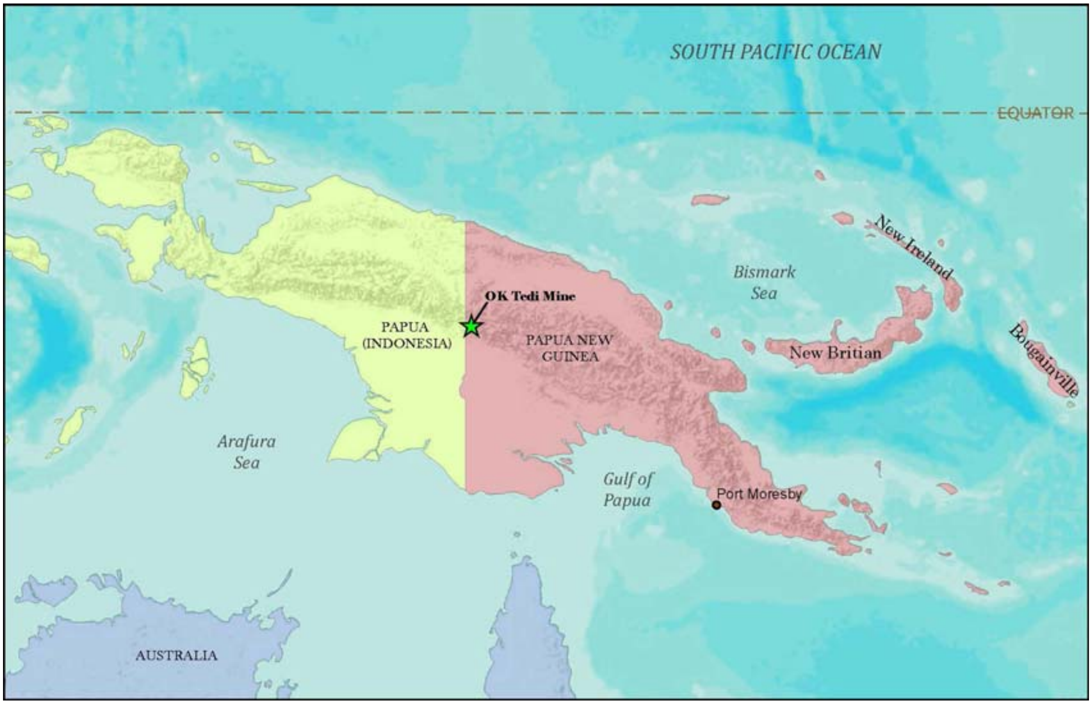


FIGURE 28.2 Map of Papua New Guinea.

Prior to gaining its independence in 1975, PNG had been ruled by three external powers for about 90 years (Fig. 28.1). Between 1885 and 1942, the country comprised two separate jurisdictions – Papua and New Guinea – ruled by Britain and Germany, respectively. Britain transferred the southern territory of Papua to Australia in 1906, and by 1942, Australia assumed control of both territories, naming the unified territory 'Papua New Guinea' in 1949 (Griffin et al., 1979; Reilly, 2008). The common languages that were developed during the German and British rule are 'Tok Pisin' and 'Motu', which are commonly spoken in the eastern and the southern region, respectively.

Despite its relatively short tenure as an independent government, PNG has been lauded as having one of the developing world's most impressive records of democratic longevity, including elections characterised by high levels of public participation and peaceful governmental transitions (Reilly, 2008). However, unlike parts of neighbouring Indonesia, there was no history of state-like organisation in the country before European contact (Griffin et al., 1979). Instead, society was and continues to comprise thousands of small, largely autonomous tribal units (clans) who developed their own languages, cultural identities and traditions (Reilly, 2008). Ethnographers have documented more than 850 living languages, making PNG the most linguistically diverse country in the world (Eberhard et al., 2021).

After nearly 50 years, nation-building and forging a collective identity is still a work in progress, and many PNG people straddle the traditions of their ancestors with the desire for improved economic and societal benefits associated with development (Oates, 2012).

While the central government plays a major role in certain functions like regulating industry and developing the fiscal regime under which taxes and royalties are paid, they struggle to deliver basic services such as education, health services, policing and community development (Banks, 2008).

The people of PNG, therefore, still depend on traditional ways for survival, and the modern state has little or no real influence in how they live their daily lives (Oates, 2012). Most communities continue to live a subsistence lifestyle, and they retain the same strong cultural connection to the land as their ancestors. This sentiment is eloquently encapsulated in a quote from Bougainville documented by Dove et al. (1974, p. 182 as cited in Banks, 2008): 'Land is our life. Land is our physical life – food and sustenance. Land is our social life; it is marriage; it is status; it is security; it is politics; in fact, it is our only world'.

Hence, 'land' (including rivers, plants, animals, fish, etc.) and all the ecosystem services it provides form the centre of the PNG societal universe. While the state legally holds mineral and timber rights, 97% of the land in PNG is held under customary tenure (Banks, 2008). This affords local communities powerful leverage in negotiations over resource developments, and in the case of mineral resources, this is negotiated through the 'Development Forum' held before mining contracts can be issued by the state government. As explained by Banks (2008, p. 25): 'In the Development Forums, communities have agreed to allow access to land in exchange for a suite of benefits – typically infrastructure, jobs, business contracts and compensation, equity in the development and royalty share. This provides communities with significant power to control access to natural resources within their territory, an unusual setting in terms of state-community power relations documented elsewhere by political ecologists'.

Perhaps, the most infamous demonstration of this power is the revolt by local communities in Bougainville that not only forced the closing of the Panguna Copper Mine but led to a 10-year civil war with up to 15,000 people dying during the conflict. While there has been much writing and debate about the conflict (e.g., Filer, 1990; Griffin, 1990; Regan, 1998; Banks, 2008; Reilly, 2008), most scholars agree that the violent rejection of the mining company, which had operated between 1972 and 1988, was borne from intractable issues associated with the distribution of benefits and the environmental impact of the mine on the local community (Banks, 2008). This incident, including the forced closure of the mine in 1989, continues to influence contemporary resource developments across PNG and how mining companies must accommodate the needs of local communities, to successfully operate (Banks, 2001).

As discussed in the following sections, the OTML mine was under development and causing environmental devastation and cultural upheaval around the same time the Bougainville revolt was brewing (Fig. 28.1; Jorgensen, 2006). However, the fate of the OTML copper and gold mine was considerably different than Bougainville's Panguna mine, driven by a confluence of events including local, national and international pressures that led to, among other things, a change in mine ownership and requirements to address environmental impacts and the concerns and needs of local communities. This confluence of events also included a wave of scientific publications in the late 1990s and early 2000s (e.g., Chapin and Starfield, 1997; Hobbs et al., 2006; SER-ISPWG, 2004; Suding and Gross, 2006; Walker and Salt, 2006) addressing resilience principles, ecological restoration and novel ecosystem concepts that strongly influenced the newly formed OTML Environment Department charged with planning, implementing and monitoring the stockpile afforestation of mine derived sand dredged from the Ok Tedi.

## The Ok Tedi mine

The Ok Tedi porphyry copper-gold-silver mine is located on Mt. Fubilan in the Western Province of PNG near the border with Indonesia (Fig. 28.3A). The mine comprises an open-pit and milling facilities that reduce the ore to concentrate. The concentrate is sent via pipeline to the river port of Kiunga, where it is loaded onto barges for shipment to the capital city of Port Moresby.

The Western Province can be divided into two regions, the mountainous north and the much more extensive area of lowland floodplains and lakes to the south. Located within the political boundary of the Northern Fly District, the Ok Tedi drains the Hindenburg Range at over 2000 m above mean sea level (masl) and flows for 200 km to its confluence with the Fly River at D'Albertis Junction at 20 masl (Fig. 28.3A). The Fly River continues south roughly 800 km before entering the Gulf of Papua.

The Ok Tedi is divided into three geomorphological zones, the Mine Area Creeks where the Ok Tedi Mine is located, the upper Ok Tedi and the lower Ok Tedi (Pickup, 2001). From its headwaters, the upper Ok Tedi flows south 70 km through steep, karst-bedrock gorge. This upper segment is fast-flowing and capable of transporting large quantities of coarse sediment, including boulders (Pickup and Marshall, 2009). The lower Ok Tedi starts just upstream from Ningerum (Fig. 28.3A) where it transitions from its gorge into a gradually

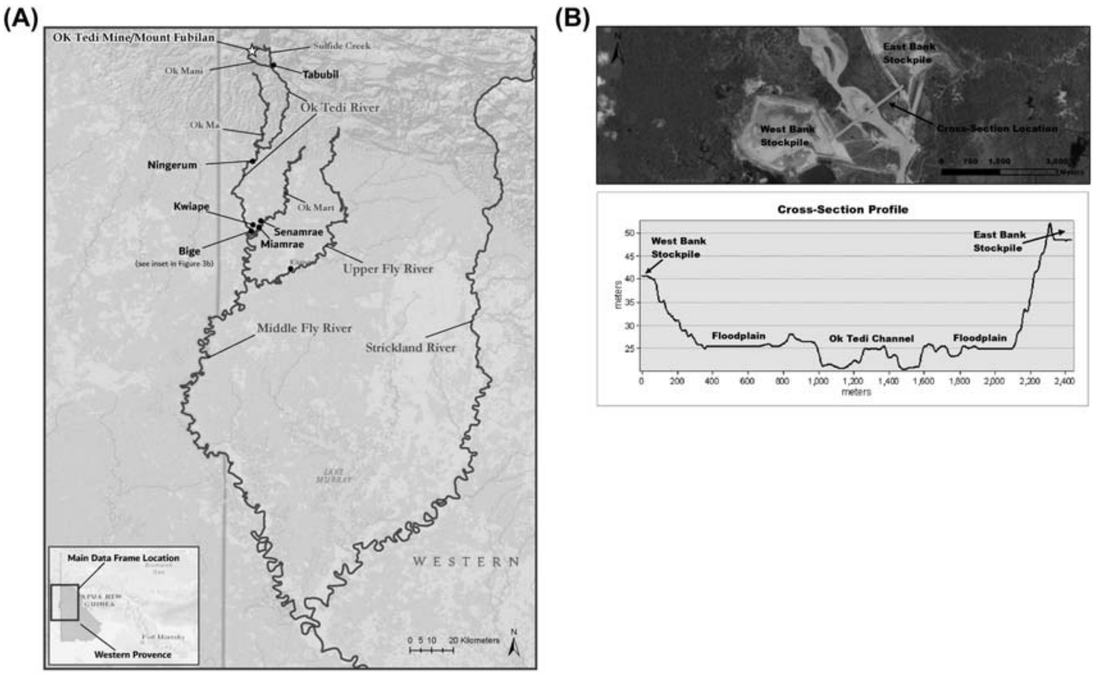


FIGURE 28.3 (A) Map of the Ok Tedi and Fly River system. (B) Plan view and cross-section view of the Ok Tedi stockpiles near Bige.

widening braided valley filled with Pleistocene alluvial deposits including weathered and indurated sand and gravel deposits (Pickup and Marshall, 2009).

Copper and gold deposits were discovered on Mt. Fubilan in 1968 by Kennecott Copper Corporation. Kennecott's efforts to develop the mine failed in the mid-1970s after several years of negotiation with the territorial government, which was in the process of transitioning from Australian rule to independence. By 1976, one year after PNG attained independence, the newly formed government entered into an agreement with a consortium led by Broken Hill Proprietary (BHP) as the majority owner (Davies et al., 1978), and by 1981, OTML was incorporated as an entity to operate the project (Griffiths et al., 2004).

Field conditions at the mine site were extraordinarily challenging, and mine infrastructure development experienced schedule setbacks from the outset. Average annual rainfall in the Highlands is approximately 10,000 mm distributed evenly throughout the year, and the area is subject to extensive seismic activity and frequent landslides (Griffiths et al., 2004). The combination of unstable and rugged terrain and heavy rainfall thwarted siting of key infrastructure, but most consequential was the landslide induced failure of the Ok Ma tailings dam and the decisions that followed to discharge mine waste rock and tailings into the river.

From the outset of the project, the PNG government required that a permanent tailing storage facility be constructed before mine operations were initiated to contain the 1100 million tonnes (Mt) of mine waste estimated at the time (Griffiths et al., 2004). Work on the Ok Ma tailings dam began in May 1983, but within a year two major landslides buried the area and destroyed any potential for building the tailings dam. In 1989, OTML successfully made the case to the PNG government that a tailings dam would be technically infeasible to build because of heavy rainfall and geologic instability (citations in Griffiths et al., 2004). This led to government approval of a riverine waste rock and tailings disposal method that continues to this day.

## Biophysical and social impacts of riverine waste rock and tailings disposal

By the 1990s, the upper Ok Tedi was receiving approximately 187 $Mm^3$ of mine waste annually compared to a natural annual sediment load of 0.11 $Mm^3$ (Hettler et al., 1997). Studies of channel morphology documented that much of the coarse waste rock is retained in the upper reaches of the Ok Tedi, while finer particle sizes (sand and silt) are transported and deposited as bedload along the lower Ok Tedi and middle Fly River (Pickup, 2001; Pickup and Marshall, 2009, Pickup and Cui, 2008). A large part of the suspended load is transported downstream where it is deposited in the Fly River delta in the Gulf of Papua (Hettler et al., 1997).

By the early 2000s, Pickup and Marshall (2009) reported that channel bed levels in the lower Ok Tedi had risen approximately 2 m above pre-project elevations at Ningerum, peaked just downstream of Bige at approximately 8 m and remained high (at about 5 m) down to the confluence with the Fly River at D'Albertis Junction (Fig. 28.3A). Major geomorphic trends along the middle Fly River included a gradual increase in channel bed elevations and a substantial increase in floodplain levee elevations that restricted lateral connectivity (via tie channels) to off-channel swamps and lakes (Pickup and Marshall, 2009).

Environmental impacts of the riverine waste rock and tailings disposal programme are well documented in a series of interdisciplinary scientific investigations compiled by the OTML Environment Department (Bolton, 2009). One of the most profound impacts was the expansive die-back of floodplain forest along the lower Ok Tedi and middle Fly River. Channel bed aggradation created persistent submersion of the floodplain and ultimately drowning of the forest vegetation (Rau and Reagan, 2008). From 1992, when the first dieback was reported to 2020, a total of 219,200 ha of floodplain forest within the lower Ok Tedi and middle Fly River was either dead or stressed (Marshall and Marshall, 2021).

The forest dieback has had a profound cultural impact on the subsistence livelihood of the Awin and Yongom communities living in the lower Ok Tedi basin (Jorgensen, 2006). The widespread dieback and shifts in forest structure and species composition has affected the availability of key forest resources used for food, housing, medicine, fuel wood and other cultural purposes. Dieback also affects habitats for game animals and wildlife that the communities rely upon for nourishment. Sago palm (*Metroxylon sagu*), a particularly important staple food item for the local Awin and Yongom people, has been severely impacted by prolonged floodplain inundation. Patches of sago palm have reduced from approximately 33,000 ha in 1982 to 19,000 ha in 2015 (Marshall and Marshall, 2021).

According to Jorgensen (2006), the impacts of forest flooding on the livelihood of the Yongom people were particularly devastating because their village distances from the mine infrastructure rendered fewer employment opportunities than for residents of the Awin villages. In the 1990s, Yongom tribal leaders obtained assistance from national nongovernmental organisations and an Australian law firm to bring a civil lawsuit against the major partner in the OTML consortium, BHP. The lawsuit received wide international attention and was settled out of court in 1996 (Fig. 28.1). The ensuing settlement provided the Yongom with a large financial award and required OTML to implement a major river dredging operation and a plethora of environmental studies and community sustainability initiatives. In 2002, BHP exited the OTML consortium, transferring their majority ownership to the newly formed PNG Sustainable Development Program (SDP). The PNG-SDP manages its share of OTML dividends with a mandate to support sustainable development plans with a special focus on communities downstream from the OTML mine (citations in Jorgensen, 2006).

Of the many important initiatives borne from the settlement, a river channel sand dredging operation was the most critical for mitigating impacts of the riverine disposal of waste rock and tailings on forest floodplain dieback. The remainder of this chapter focusses on the evolution of a rehabilitation program developed by OTML to create a resilient native forest on the sand stockpiles created through the sand dredging operation.

## Mitigating impacts of river channel aggradation

To mitigate impacts of riverbed aggradation and its effects on floodplain forest dieback and associated loss of cultural and biological resources, a continuous river channel dredging operation commenced in 1998 (Fig. 28.1). The dredging site is located near the village of Bige approximately 100 km downstream of the mine site (Fig. 28.3A). This site was selected because it is the approximate upstream extent of the forest floodplain die-back and is located at the transition zone where the river channel changes from a braided gravel-bed to a meandering sand-bed channel.

The objective of the dredge operation is to remove up to 10 $Mm^3$/year of mine derived sediments from the river channel and to store the material in engineered stockpiles over the submerged floodplains on the east and west banks of the river channel (KCB, 2006a). The construction of the East Bank stockpile began in 1998 along with experimental revegetation trials using a mixture of native and non-native tree species. Construction of the West Bank stockpile commenced in 2004. Dredged sediments are composed primarily of sand size particles derived from a mixture of mine tailings, waste rock fines, natural sediments from landslides and bank erosion and resuspended alluvium (OTML, 2007).

After dredging the river for about eight years, studies by OTML determined that the dredged sand was potentially acid generating (PAG) and the acidity of future tailings was projected to increase over time. Other studies conducted by the mine (EGi, 2006; KCB, 2006b) indicated that the acid rock drainage (ARD) potential of the dredged sand could be substantially reduced if the tailings could be continually saturated and if the PAG dredged sand could be covered with 3–4 m of non-acid generating (NAG) dredged sand to serve as an oxygen barrier and growth media (EGi, 2007; OTML, 2007).

To reduce the release of PAG tailings to the Ok Tedi, in 2009, OTML implemented a flotation circuit at the Fubilan mill to extract most of the sulfide minerals such as pyrite from the tailings prior to riverine discharge. Crushed limestone is also added to the mill as part of the feed to raise the acid neutralising capacity of the tailings prior to it being released into the Ok Tedi headwater tributaries (OTML, 2007). The tailings pH and sulphur concentrations are monitored daily prior to discharge to ensure that the tailings meet NAG criteria. The pyrite concentrate (PCon) is then sent to Bige via pipeline for subaqueous burial into disposal cells at the West Bank stockpile (KCB, 2006a). The reactive PCon material is stored at depth below the natural ground water level within the interior of the West Bank stockpile, which prevents acid generation by keeping the PCon saturated (KCB, 2006b).

The general stockpile design and construction involves hydraulically depositing the dredged sand onto the centre of the stockpile where the depth to the piezometric surface is lower than near the stockpile crests, thereby maximising PAG sand saturation (KCB, 2006). The PAG sand is then covered with 3–4 m of NAG sand dredged from river as explained earlier. This NAG 'cover material' serves as a substrate for planting forest vegetation. Once fully constructed, the stockpiles will span an estimated 1000 ha with the top surface resting approximately 20 m above the natural ground elevation (Fig. 28.3B; OTML, 2007).

## Bige stockpiles: A novel ecosystem

The Bige stockpiles were first constructed in the early 2000s when the scientific community was developing philosophical and practical frameworks for ecological restoration, including differentiating between *restoration*, *rehabilitation* and *reclamation*. At the time, the working definitions developed by the Society for Ecological Restoration (SER) for both *restoration* and *rehabilitation* were that they shared a fundamental focus on returning a disturbed area to historical or pre-disturbance conditions (cf. SER-ISPWG, 2004; Gann et al., 2019). The definitional differences between the two were relatively vague, suggesting that both are concerned with ecosystem processes, productivity and services, but unlike *rehabilitation*, *restoration* was concerned with a return to some resemblance of historical species composition and structure. *Reclamation*, which they associated primarily with mined lands, was considered principally concerned with stabilising terrain, assuring public safety and based on their assertion that reclamation plantings only involved one or a few species (SER-ISPWG, 2004), had less interest or focus on ecosystems or biotic integrity.

Management objectives for the dredged sand stockpiles at Bige do not fit neatly into any of these definitions. Stabilising the terrain and assuring public safety (i.e., reclamation) are absolute priorities, but achieving OTML objectives over the long-term require successful establishment of a variety of plant species (rather than 'one or a few'). Returning the site to historical or *pre-disturbance* conditions (i.e., restoration) also does not fit because the dredged sand stockpiles comprise mine-derived sediments that never previously supported vegetation.

Indeed, the stockpile rehabilitation programme is an *afforestation* programme that involves building a new forest on dredged sand substrate that is not soil (GSA, 2013). The Bige dredged sand stockpiles are primarily crushed rock particles that differ physically, chemically and biologically from the natural soil conditions of the surrounding lowland tropical forest. Compared to local PNG soils the dredged sand.

- Contain less silt and clay, have lower water holding capacity and have variable hydrologic and drainage characteristics.
- Have alkaline pH ($\geq$ pH 8) values instead of acidic pH (pH $\leq$ 5) values of local soils.
- Have low concentrations of organic carbon (OC, <1%) and total nitrogen (TKN, <250 mg/kg) compared to local soils (OC = 3%−10%, TKN = 1600−8600 mg/kg).
- Have elevated bioavailable concentrations of phytotoxic metals, particularly copper and zinc.

Finally, the construction of the stockpiles results in land surface elevations that are up to 25 m above the pre-disturbance ground level (Fig. 28.3B), resulting in increased depths to groundwater that can negatively affect plant water availability. Depending on the location along the stockpile, predicted depth to groundwater can range from approximately 1 m to over 4 m in depth; these depths can greatly fluctuate in response to precipitation rates. By comparison, typical depth to groundwater in the surrounding lowland soils are less than 1 m (GSA, 2013).

Acknowledging these fundamental differences between the stockpiles and the surrounding tropical forest enabled OTML to recognise the stockpiles as a 'novel ecosystem' (NRA, 2009). Initially coined by Chapin and Starfield (1997) and expanded upon by others (e.g., Hobbs et al., 2006; Hobbs et al., 2009; Morse et al., 2014), the basic premise of novel ecosystems is they have been fundamentally altered by intentional (e.g., open pit mining, large flood control dams) or unintentional (e.g., climate change) human activities so that biotic and/or abiotic thresholds have been irreversibly crossed, rendering a return to pre-disturbance conditions as neither functionally nor practically attainable. Instead of emphasising the return to historic conditions, rehabilitation of novel ecosystems requires: (a) acknowledging that ecosystem thresholds have irreversibly crossed into a new 'basin of attraction' (Chapin et al., 2009); (b) working to understand properties, services and functions of these systems, and; (c) applying adaptive ecosystem management so that the trajectories and desired outcomes of these systems can be proactively managed (Hulvey et al., 2013; Lindenmayer et al., 2008; Suding and Gross, 2006; Seastedt et al., 2008).

The fact that the dredged sand stockpiles are a novel ecosystem led OTML to place greater emphasis on addressing ecosystem functions and cultural values rather than striving for some fixed forest compositional and successional pathway dictated by a non-existent reference condition. As noted by Seastedt et al. (2008), in managing novel ecosystems, the point is not to think outside the box but to recognise that the box itself has moved.

## The rehabilitation framework

Pioneering studies on novel ecosystems by Hobbs et al., (2006), Suding and Gross (2006), Suding and Hobbs (2009), Seastedt et al. (2008) and the SER guidebook (SER-ISPWG, 2004) strongly influenced the framing of the stockpile afforestation programme and is evident by frequent citations in OTML's (2009) Mine Area Rehabilitation Plan (OTML, 2009). The Ok

Tedi rehabilitation framework and its rationale came about during working sessions in which environmental managers and their science advisors defined the core stockpile rehabilitation objectives, identified risks and thresholds to achieving those objectives, identified management programme components required to achieve success and addressed attributes of rehabilitated ecosystems suggested by SER (NRA, 2009).

The core stockpile rehabilitation objectives identified (NRA, 2009; OTML, 2009) include.

- Minimise ARD development and metal leaching through the provision of a geochemically stable cover over the existing stockpile material.
- Minimise erosion to ensure the long-term integrity of the geochemical cover.
- Provide soil surface protection and vegetation cover that maximises the likelihood of maintaining the integrity of ARD mitigation measures in the long term.

To realise these objectives, the planning team determined that the vegetation cover on the stockpiles must be (NRA, 2009).

Self-sustaining: The created forest, after a period of establishment, is *ecologically resilient* by maintaining required productivity levels, successional processes and nutrient cycling over the normal disturbance cycles (fire, climatic events, predation, and sporadic, small-scale disturbances associated with indigenous management practices) without further active management intervention.

Acceptable to the local landholders: The created forest, after a period of establishment, is *socially resilient* by being positively valued by local human inhabitants. There is a need to prevent a situation where the forest rehabilitation is not valued sufficiently by the local people and is subsequently destroyed or modified to create an alternative land use that may not afford the surface protection required to maintain the integrity of the ARD mitigation measures.

## Conceptual model for creating a resilient forest

The mission of establishing a self-sustaining tropical forest ecosystem on a substrate comprised of mine-derived sand dredged from the Ok Tedi is daunting, yet field observations of stockpile conditions provided reasons for optimism. For example, BioTropica (2009) observed significant patch diversity at two locations on the East Bank stockpile where topsoil from adjacent forest had been placed in small ($\sim 5\ m^3$) mounds. They noted 'these topsoil dumps were islands of diversity in an otherwise sterile area on the top of the east bank stockpiles. An opportunistic survey of the soil piles recorded 18 native plant species across a range of families, life forms (trees, shrubs, vines, ferns, scramblers) and successional stages. Plants were well established, with some individuals up to 5 m tall, indicating that some root systems may extend into the dredge spoil below. It is most likely that the species within these patches were present within the soil seed bank and germinated once the spoil pile had been deposited. However, the importance of diversity in plant species, life form and structure for building ecosystem complexity was reinforced by observations of native fauna at topsoil sites. Native finches were observed in active nests and breeding within both patches, and survey in one patch revealed 12 morphospecies of invertebrates from seven different Orders' (BioTropica, 2009, p.2).

These observations indicated that rehabilitation techniques focussing on soil development may constitute the type of positive feedback needed to facilitate natural recruitment and successional processes associated with a resilient forest (Lamb et al., 2005; GSA, 2013). With very limited sources of topsoil or other organic materials to spread across the vast stockpile surface, it was determined that the revegetation strategy should focus first on identifying regionally native ‘pioneer’ forest species, that is, those capable of establishing, surviving and growing on the stockpile with little or no organic amendments. Successful pioneer forest plants would not only stabilise the highly erosive dredged sand stockpiles, but root development and leaf litter deposition would facilitate nutrient cycling and development of microbiota that recycle carbon compounds, assist plants with mineral nutrient uptake and promote forest succession (GSA, 2013). This aspect of the rehabilitation has a focus on slow variables (Walker and Salt, 2006) and their importance to increasing landscape resilience.

Thus, the conceptual model (Fig. 28.4) adopted by OTML was that pioneer species would facilitate soil development via root penetration (physical structure and exudates), leaf litter deposition and decomposition and provide shading for successional plants. Key to the process of converting a sterile, alkaline and sandy substrate with limited nutrient cycling into a soil capable of supporting a broad variety of successional forest species is to generate a surface organic layer that will support a microbial community (fungi, bacteria, macro- and micro-invertebrates) and ongoing pedological development (Goosem and Tucker, 1995; Lamb et al., 2005; Harantova et al., 2017). Based on observations from early field trials (LRS, 2007), it was envisioned that a broader variety of early to mid-successional (*framework*) species could be planted within 5 years, and if necessary, later successional (*maximum diversity*) species could be added if monitoring indicated a lack of natural recruitment within the envisioned 15-to-20-year active management time frame (BioTropica, 2009; NRA, 2009).

With this conceptual model, OTML and its advisors began compiling lists of locally and regionally native forest species and organising them based upon autecological characteristics (BioTropica, 2009). This effort culminated in a list of 194 species organised into what Goosem and Tucker (1995) refer to as ‘plant functional groups’ (Table 28.1). The next step would be to combine species characteristics with knowledge of plant cultural use values and other factors to create a ranking system for prioritising propagation and initiating planting trials.

## Integrating cultural values

A critical step in applying resilience thinking to the rehabilitation of social−ecological systems involves bringing together stakeholders to determine components that make up the system and interconnections (Walker and Salt, 2012). Rehabilitation approaches that fail to involve local peoples or take account of their various interests are unlikely to succeed (Lamb and Gilmour, 2003). Given the strong reliance on forest resources by local communities and a commitment by OTML to accommodate their needs, ethnobotanical investigations were initiated in 2008 to integrate indigenous knowledge and uses of forest plant species into the stockpile revegetation programme (Butler et al., 2012; NRA, 2011).

OTML’s ethnobotany investigation (NRA, 2011; Butler et al., 2012) involved a series of interviews, meetings and field surveys with men and women of different age groups from the East Bank villages of Miamrae, Kwiape, Bige and Senamrae (Fig. 28.3A). The investigation sought to understand and document plant names (local and scientific), plant characteristics/life-form (tree, shrub, vine, palm, herb, etc.), local uses, frequency of use and the species’ relative abundance/scarcity in the local forest. In all, 190 locally used species or locally recognised plant types representing 62 families were recorded (NRA, 2011). Documented plant uses included structural materials for buildings (e.g., support posts, rafters, flooring, roofing), canoes, foods, medicines, food resources for game and other animals and a variety of other miscellaneous uses (e.g., hunting and weapons, clothing, pigments, cleaning, fuel, insect repellents, lighting, cooking, tools, musical instruments, spiritual).

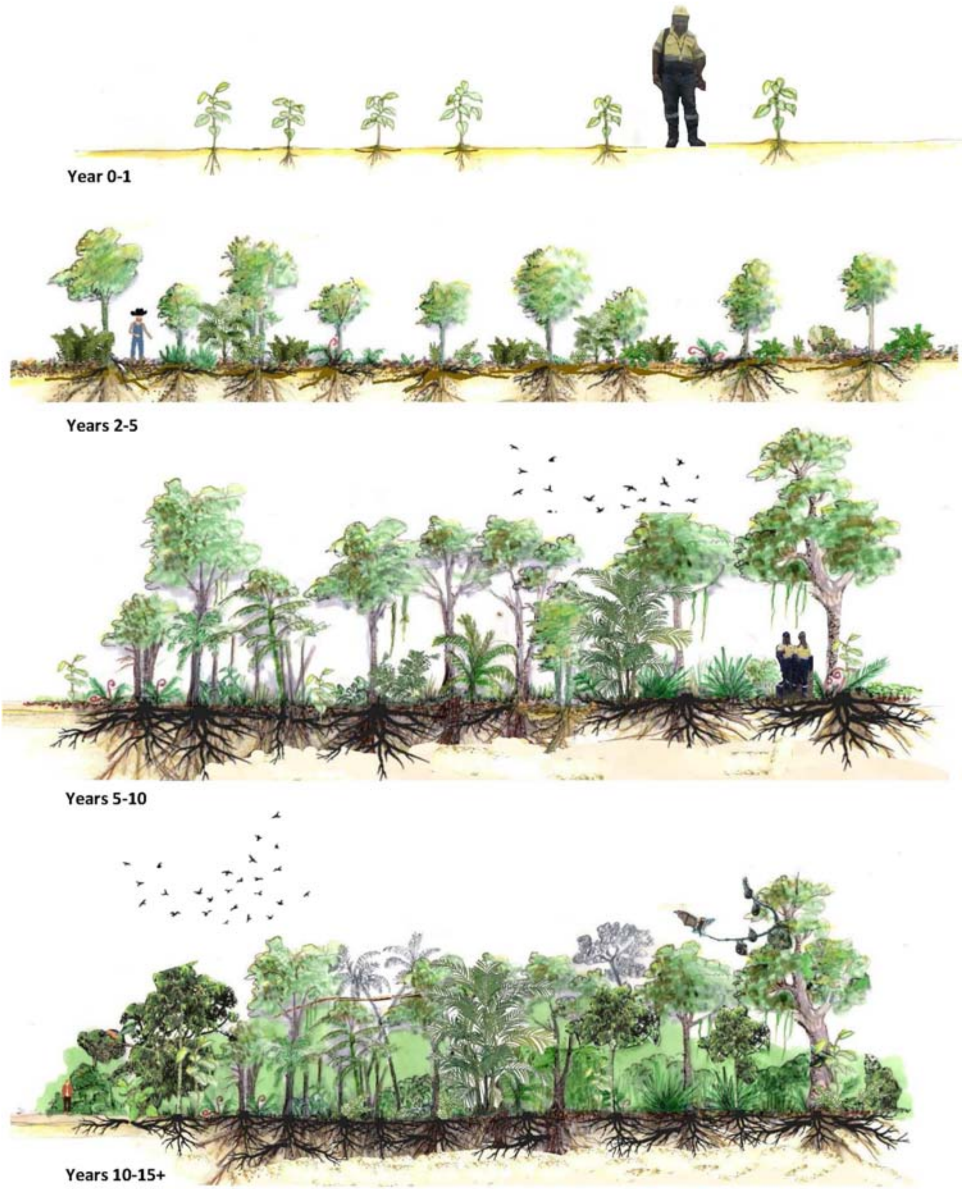


FIGURE 28.4 Conceptual model illustrating progressive soil and forest development over 15-to-20-year. *Illustration credit: Georganna Collins, Aqua Strategies Inc.*

## Ranking species for nursery propagation and revegetation

To prioritise species for different stages of revegetation, plant species were first assigned to different functional groups (Table 28.1) and then ranked using a multi-criteria analysis

TABLE 28.1 Functional planting groups.

| Functional group | Typical traits | Examples |
|---|---|---|
| **1.** Pioneer species | • Tolerant of open and/or degraded conditions<br>• Small seeds, long lived<br>• Early successional species<br>• Treatment required to stimulate germination<br>• Generalist dispersal vectors<br>• Disturbance adapted | • *Acacia* spp.<br>• *Alphitonia macrocarpa*<br>• *Macaranga* spp. |
| **2.** Framework species | • Tolerant of open and/or degraded conditions<br>• Occur across successional stages<br>• Seeds easily germinated<br>• Attractive to many frugivorous dispersal vectors<br>• Contribute to natural regeneration away from the planting site | • *Ficus* spp<br>• *Homalanthus novoguineensis*<br>• *Pometia* spp. |
| **3.** Maximum diversity | • Intolerant of open and/or heavily degraded conditions<br>• Typically late successional species<br>• Shade tolerant<br>• Specialised dispersal vectors<br>• Specialised life forms (e.g., aroids)<br>• High ethno-botanical value | • *Garcinia* spp.<br>• *Horsfieldia* sp. |

*Modified from BioTropica (2009).*

(MCA) that considered three factors: (1) cultural significance, (2) tolerance to open/degraded areas and (3) ease of nursery propagation (BioTropica, 2009; NRA, 2011). Cultural significance was determined using a Cultural Significance Index (CSI) following procedures described by NRA (2011) and Butler et al. (2012). Each of the three factors were evenly weighted (score range 0–3) for a maximum score of 9. These MCA scores were used to prioritise species in each functional group for nursery propagation and revegetation (BioTropica, 2009; NRA, 2011).

In 2009, OTML constructed a forest plant nursery that included a greenhouse, seed treatment facilities, benches for potting, propagation tunnels and outdoor growth areas (BioTropica, 2009). Over the next several years, seeds for both pioneer and framework species were gathered locally or obtained from commercial sources. Seed germination, viability and storage tests were performed and documented (NRA, 2012). Greenhouse and small-scale field trials were conducted to evaluate which species could be successfully established on unamended dredged sand through direct seeding versus potted plant material ('tubestock'), while other experiments evaluated root colonisation by nitrogen fixing bacteria, the effects of various green-waste compost amendments on tubestock biomass and survival and growth rates of species planted on stockpile slopes and top surfaces.

## Stockpile rehabilitation and afforestation techniques

The first revegetation trials initiated in 1998 at the base of the East-Bank stockpile involved spreading woodchips across the ground surface, seeding an herbaceous cover crop and planting nursery raised saplings ('tubestock') of native and non-native (e.g., *Leucaena*


FIGURE 28.5 Representative photographs of OTML hydroseeding batter slopes (left) and resulting vegetation growth 18 months later (right).

*leucocephala*) trees (LRS, 2007). By 2009, OTML officially discontinued using non-native trees and initiated hydromulching experiments on stockpile slopes using a slurry composed of a bonded-fibre matrix (BFM) and seed from several regionally native pioneer species (*Acacia* spp., *Paraserianthes falcataria*, *Casuarina* spp.; Fig. 28.5A).

Stabilising the highly erosive sand stockpile, however, required modifying the slope design from a traditional 3H:1V bench and batter design to a more gradual 15H:1V slope to reduce rainwater drainage velocity, erosion and hillslope gully formation. The updated slope design (KCB, 2014) incorporates soft engineering water management features including vegetated drainage swales to direct rainwater off the slopes. Although the BFM hydromulching techniques have demonstrated promising results (Fig. 28.5B), revegetation techniques on the swale slopes shifted to spreading woodchips across the ground surface, hand seeding the same species used in the BFM slurry, and planting tubestock of 15–20 different native pioneer and framework tree species (Fig. 28.6). This technique continues to be applied on West-Bank swales, although limited woodchip supplies require opportunistically

FIGURE 28.6 Photograph of OTML rehabilitation crews planting nursery raised native trees into non-acid generating dredged sand covered with a veneer of pulverised woodchips.

substituting other organic ground cover materials such as leaves from locally harvested sugar cane (*Saccharum officinarum*). Planting techniques on the flat stockpile top surface have to date not included spreading woodchips or other organic material because pluvial ponding can cause these materials to float and redistribute. Over the past 3 years (2018−2021), OTML has experimented with different tubestock planting techniques including filling planting holes with limited available supplies of topsoil or composted woodchips.

## Measuring rehabilitation success of a novel ecosystem

### Defining success

A key issue in quantifying 'success' in novel ecosystem rehabilitation is the absence of a natural reference. Published literature addressing novel ecosystems often focuses on defining novelty and recommending steps for determining novel conditions rather than discussing alternative approaches to defining and measuring success when no representative reference site exists (e.g., Doley et al., 2012; Doley and Audet, 2013; Hobbs et al., 2006; Hobbs et al., 2009; Hulvey et al., 2013; Morse et al., 2014). This was a particularly challenging issue for OTML because published monitoring methodologies under consideration (e.g., Kanowski et al., 2008; Eyre et al., 2015; Tongway and Hindley, 2004) all discuss the importance of utilising biophysical attributes of reference (analog) sites to set threshold targets (endpoints) for determining rehabilitation success.

Although novel systems lack representative analogues for guiding post-rehabilitation targets, this should not be used as an excuse for lowering rehabilitation standards (Bridgewater and Yung, 2013; Perring et al., 2013). An alternative approach is that success could be measured by demonstrating trajectories in the performance of key ecological functions without committing to an arbitrary endpoint (Choi, 2007; Gwenzi, 2021; Hughes et al., 2011; Suding and Gross, 2006). Informed by monitoring, adaptive management is implemented to make 'corrections' when desired trajectories are heading off-track, and in some instances, to re-calibrate assumptions about the speed and/or slope of those trajectories (Hulvey et al., 2013; Suding and Gross, 2006).

OTML embraced this ecological functional trajectory concept as the guiding principle for evaluating stockpile rehabilitation success. In other words, rather than selecting an arbitrary quantitative endpoint, success would be determined based on a progressive upward trajectory in ecosystem functional performance over time. The monitoring programme would focus on evaluating attributes of various ecosystem functions, particularly those that could be tied directly to the overarching rehabilitation objectives and implementation framework described previously.

Emphasising ecological functions rather than biological composition for ecosystem management is an important tenant of *resilience thinking*. Indeed, resilience is the capacity of a system to reorganise, adapt and transform following disturbance or to move between alternate system states without changes in system function (Holling, 1973; Gunderson et al., 2012; Walker and Salt, 2006). So, while the species composition of an ecosystem is commonly held up as criteria for success, it is ecosystem structure and functions, rather than species composition per se, that need to be resilient if ecosystem services are to be maintained (Oliver et al., 2015).

## Measuring success

By 2016, OTML determined that the Ecosystem Function Analysis (EFA) monitoring methodology (Tongway and Hindley, 2003, 2004) would enable the assessment of functional trajectories while also aligning well with many of the stockpile rehabilitation objectives (OTML, 2009). Although all methods have their advantages and disadvantages, EFA monitoring was chosen because: (1) the procedures emphasised soil-based ecological functions relevant to reclamation of Bige stockpiles, (2) results from surrogate field measurements have demonstrated strong correlations to in-situ field and laboratory measurements across a variety of ecosystems, including tropical forests (northern Queensland, Philippines, Indonesia; Tongway and Hindley, 2004), (3) analytical outputs display function score trajectories over time and (4) field procedures are relatively rapid and cost-effective and could be implemented in remote locations with minimal equipment.

EFA evaluates performance of three ecosystem functions, namely 'soil stability', 'nutrient cycling' and 'infiltration'. Tongway and Hindley (2004) describe each function as follows.

- Soil stability is defined as the ability of the soil to withstand erosive forces and to re-form after disturbance.
- Infiltration is defined as how the soil partitions rainfall into soil–water (water available for plants to use), and runoff water, which is lost from the local ecosystem, or may also transport materials (soil, nutrients and seed) away.
- Nutrient cycling is defined by how efficiently organic matter and nutrients are cycled back into the soil.

Each of these functions is comprised of multiple attributes that are measured along permanent transects (Fig. 28.7). An obvious shortcoming of the standard EFA approach (Tongway and Hindley, 2004) is that it does not directly address functional attributes associated with vegetation (Humphries, 2015). Tongway and Hindley (2004) provide examples of additional vegetation monitoring methods but acknowledge that each biogeographic area needs to develop its own indicators that reflect locally appropriate conditions and success criteria. Accordingly, given the strong emphasis on developing resilient tropical forests of high cultural value, OTML developed its own vegetation-based functions to evaluate whether these objectives are being met. These new functions were designed to numerically score processes associated with 'Forest Succession', 'Forest Structural Complexity' and 'Cultural Value' (GSA, 2019).

- The Forest Succession function tracks attributes associated with recruitment, growth and composition of tropical forest plant species across the rehabilitation area over time. The individual attributes that cumulatively comprise this function (Fig. 28.8) were chosen based on published literature addressing successional theory (Gibson and Brown, 1985) and research documenting tropical forest successional processes (Arroyo-Rodríguez et al., 2017; Chazdon et al., 2010; Lohbeck et al., 2013; van Breugel et al., 2007).

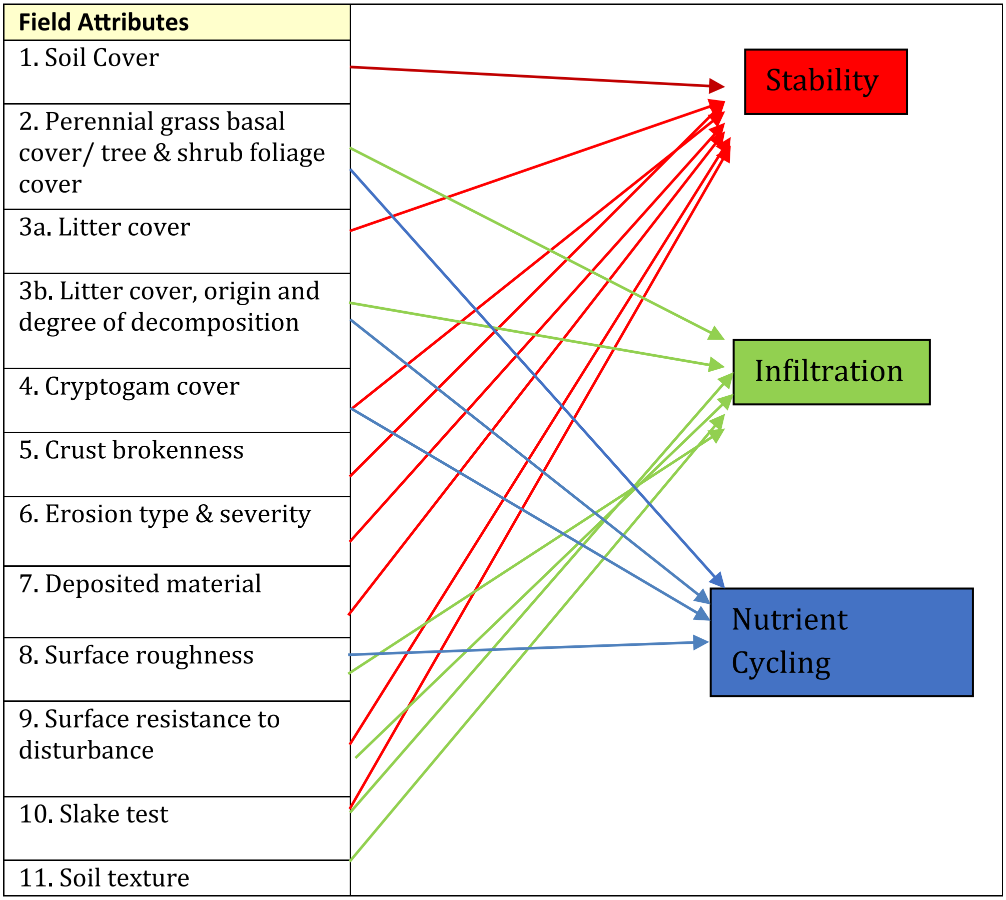


FIGURE 28.7 EFA field attributes associated with stability, infiltration and nutrient cycling functions. *From Tongway and Hindley (2004).*

- The Forest Structural Complexity function tracks attributes associated with tropical forest biodiversity. In forest ecosystems, biological diversity (a core attribute of resilient ecosystems; Folke et al., 2004) is commonly estimated by measuring attributes associated with forest vegetation structure, function and compositional complexity (McElhinny et al., 2005). Field attributes that comprise the *Forest Structural Complexity* function (Fig. 28.8) were selected based on published research demonstrating relationships between these attributes and direct measures of bird, mammal and ant diversity in moist tropical forest ecosystems (e.g., Wilson, 1959; Schulze et al., 2004; Williams et al., 2002; McElhinny et al., 2005; Oliver et al., 2014). The chosen attributes were also cross-referenced with other forest monitoring protocols (e.g., Kanowski et al., 2008; Neldner and Ngugi, 2014; Eyre et al., 2015) to further validate their inclusion.
- Cultural Value is designed to track the presence, proportion and progressive increase or stabilisation of species of known cultural value through the life of the monitoring

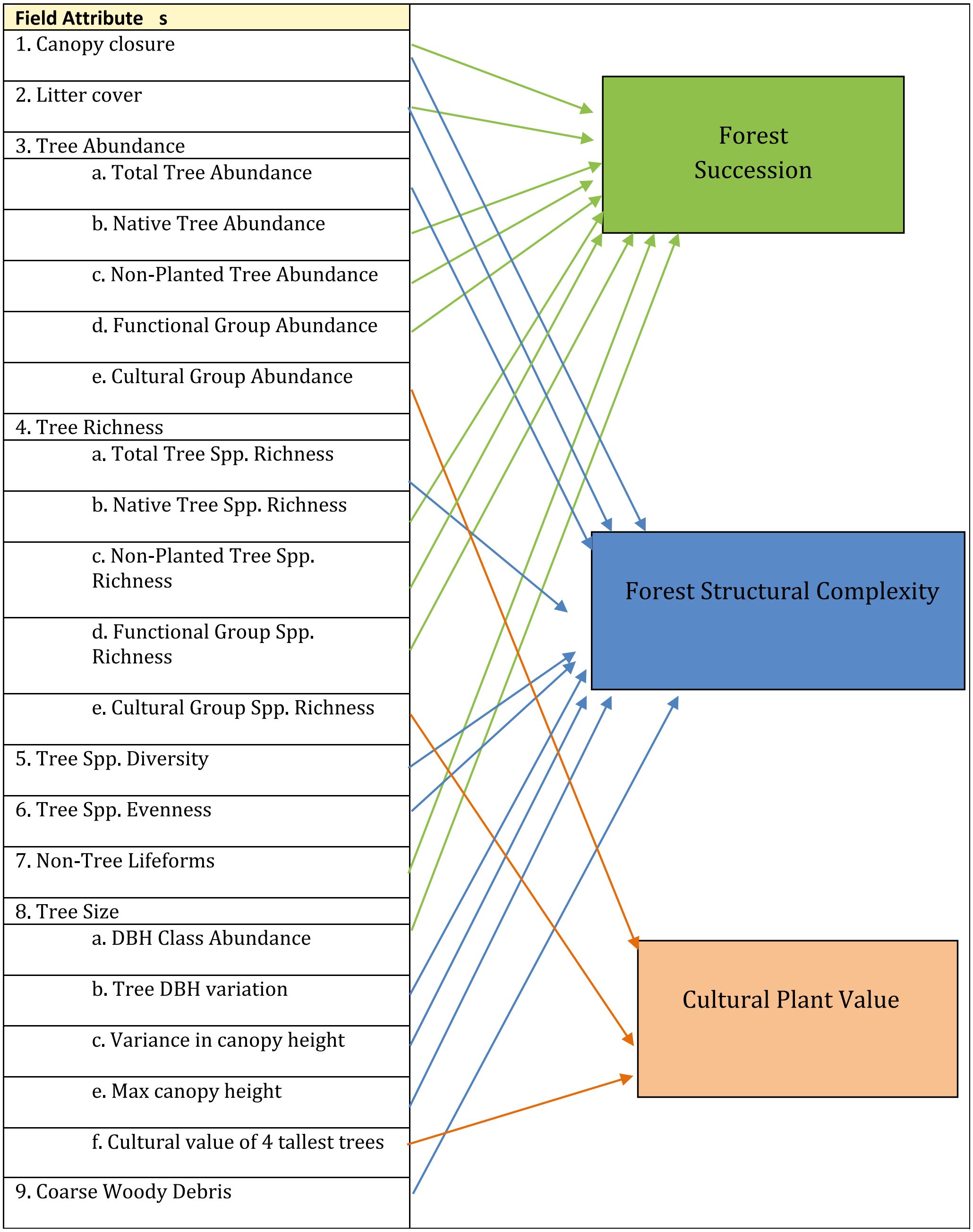


FIGURE 28.8 EFA field attributes associated with forest succession, forest structural complexity and cultural plant value functions.

programme. The ethnobotany work described previously included a numerical ranking whereby individual tree species were assigned a score of 0 through 3, where 0 = no/unknown value, 1 = low value, 2 = medium value and 3 = high value (BioTropica, 2009). These numerical rankings were integrated into mathematical algorithms for three attributes that collectively comprised a *Cultural Value* function: (1) the proportional abundance of all plants within different cultural rank categories; (2) the proportional richness (number of species) of plants within different cultural value rank categories and (3) the average cultural ranking for the four largest trees (Fig. 28.8).

Like the soil-based functions developed by Tongway and Hindley (2004), attributes associated with each vegetation-based function are measured in the field along permanent transects. Each EFA function can score in a range between 0 and 100, so with six functions the maximum potential score for the OTML monitoring programme is 600. Some attributes associated with soil-based functions have stronger mathematical influence over function scores (e.g., litter cover, origin and degree of decomposition has proportionally greater influence over Infiltration and Nutrient Cycling function scores than other attributes). For the vegetation-based functions, all attributes are evenly weighted per McElhinny et al. (2005). Mathematical formulas for all six EFA functions are presented in GSA (2021).

EFA monitoring along the stockpile slopes and top surfaces involves randomly establishing permanent transects within 6 months after initial revegetation. Data collection is scheduled to be repeated 1, 2, 3, 5, 7, 10, 15 and 20 years after initial rehabilitation. In addition to collecting EFA attribute data, monitoring procedures for all transects involve collecting physical soil samples for laboratory analysis when transects are first established (Monitoring Year Zero [MY-0]) and repeated in MY-5, MY-10, MY-15 and MY-20 (GSA, 2019). Soil samples are also collected from transects established in the areas first revegetated in 1998 ('East Bank Reference') and from a nearby undisturbed rainforest area ('KK Reference').

Soil samples are analysed in the OTML laboratory for particle-size distribution (PSD), pH, electrical conductivity (ECe), total sulphur, acid neutralisation capacity and total copper (Cu), cadmium, lead and zinc. Samples are also sent to an outside laboratory for analysis of soil nitrogen (ammonia, nitrite, nitrate and total), total organic carbon, moisture content and extractable metals (copper, zinc, iron, manganese).

## Preliminary monitoring results

### EFA monitoring

The EFA monitoring programme was initiated in 2017 (Fig. 28.1), approximately eight - months after stockpile afforestation commenced in earnest. Between 2017 and 2021, more than 60 EFA transects have been established on slopes of the West Bank and East Bank stockpiles and in revegetated zones across the top surface of the East Bank stockpile. To date, the only rehabilitation area with five years of EFA monitoring data are the swales established in 2016 along the lower slopes of the West Bank stockpile. Rehabilitation treatments within the 2016 West Bank swales involved spreading woodchips across the ground surface, hand seeding seven native species and planting tubestock of 19 native tree species (Table 28.2). Trees were planted at an average spacing of 2.5 m apart (~1600 plants/ha).

Early results from EFA monitoring of 2016 West Bank swales indicate that ecological function trajectories associated with soil development are advancing as predicted by the

**TABLE 28.2** Tree species abundance documented along eight long-term monitoring transects on the lower slopes of the West Bank stockpile (site WB Swale 2016).

| | Tree species | Number planted[a] | Seeding rate (g/ha) | Functional group | Cultural rank | Monitoring year | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | 1 | 2 | 3 | 5 |
| Planted/seeded | *Glochidion insectum* | 1458 | 0 | 2 | 3 | 20 | 60 | 93 | 128 |
| | *Nauclea orientalis* | 1149 | 0 | 2 | 2 | 23 | 26 | 6 | 3 |
| | *Glochidion novoguineense* | 1048 | 0 | 2 | 3 | 56 | 63 | 102 | 139 |
| | *Acacia auriculiformis* | 991 | 750 | 1 | 3 | 320 | 87 | 48 | 40 |
| | *Timonius timon* | 827 | 0 | 2 | 2 | 46 | 126 | 120 | 88 |
| | *Macaranga aleuritoides* | 705 | 0 | 1 | 1 | 8 | 22 | 38 | 14 |
| | *Ficus adenosperma* | 636 | 0 | 2 | 1 | 321 | 156 | 51 | 31 |
| | *Paraserianthes falcataria* | 619 | 750 | 1 | 3 | 25 | 10 | 12 | 4 |
| | *Planchonia papuana* | 282 | 0 | 2 | 2 | 2 | 0 | 1 | 0 |
| | *Gymnostoma papuana* | 270 | 0 | 1 | 3 | 5 | 5 | 4 | 7 |
| | *Premna serratifolia* | 251 | 0 | 2 | 3 | 5 | 7 | 3 | 4 |
| | *Casuarina oligodon* | 173 | 100 | 1 | 3 | 9 | 1 | 1 | 0 |
| | *Macaranga mappa* | 144 | 0 | 1 | 1 | 4 | 3 | 0 | 0 |
| | *Homalanthus novoguineensis* | 106 | 0 | 1 | 1 | 1 | 9 | 1 | 3 |
| | *Acacia mangium* | 77 | 100 | 1 | 3 | 18 | 5 | 1 | 0 |
| | *Casuarina grandis* | 24 | 100 | 1 | 3 | 54 | 0 | 0 | 0 |
| | *Ficus copiosa* | 22 | 0 | 2 | 3 | 2 | 0 | 0 | 2 |
| | *Acacia crassicarpa* | 16 | 100 | 1 | 3 | 9 | 0 | 1 | 0 |
| | *Ficus congesta* | 4 | 0 | 2 | 1 | 1 | 0 | 0 | 0 |
| | *Acacia simsii* | 0 | 100 | 1 | 3 | 71 | 0 | 0 | 0 |
| Natural recruitment | *Ficus pungens* | 0 | 0 | 2 | 1 | 1 | 0 | 0 | 0 |
| | *Octomeles sumatrana* | 0 | 0 | 2 | 2 | 1 | 0 | 0 | 0 |
| | *Neonauclea* sp | 0 | 0 | 1 | 2 | 0 | 0 | 21 | 0 |
| | *Macaranga papuana* | 0 | 0 | 1 | 1 | 0 | 1 | 1 | 1 |
| | *Piper aduncum*[b] | 0 | 0 | 1 | 0 | 0 | 0 | 51 | 15 |
| | *Neonauclea purpurea* | 0 | 0 | 1 | 2 | 0 | 0 | 0 | 15 |
| | *Anthocephalus* sp | 0 | 0 | 2 | 2 | 3 | 0 | 0 | 0 |
| | *Ficus tinctoria* | 0 | 0 | 2 | 1 | 9 | 1 | 1 | 2 |

**TABLE 28.2** Tree species abundance documented along eight long-term monitoring transects on the lower slopes of the West Bank stockpile (site WB Swale 2016).—cont'd

| Tree species | Number planted[a] | Seeding rate (g/ha) | Functional group | Cultural rank | Monitoring year | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | 1 | 2 | 3 | 5 |
| *Ficus benjamina* | 0 | 0 | 2 | 1 | 1 | 0 | 1 | 0 |
| *Neonauclea* sp | 0 | 0 | 1 | 2 | 0 | 0 | 4 | 0 |
| *Alstonia spectabilis* | 0 | 0 | 2 | 1 | 1 | 0 | 0 | 0 |
| *Acacia* sp | 0 | 0 | 1 | 3 | 0 | 0 | 0 | 1 |
| *Macaranga corymbosa* | 0 | 0 | 2 | 1 | 0 | 1 | 0 | 0 |
| *Orania cf lauterbachiana* | 0 | 0 | 2 | 1 | 0 | 0 | 0 | 3 |
| *Mallotus japonicus* | 0 | 0 | 3 | 3 | 0 | 0 | 0 | 2 |

[a]*Nursery grown, containerised sapling.*
[b]*Invasive, non-native species.*

conceptual model (Fig. 28.4). Placing woodchips across the ground surface initially elevated the soil-related function scores, and by MY-5, most of the woodchips had decomposed and ground cover was dominated by leaf litter generated by planted trees and naturally established native herbaceous plants (Fig. 28.9). Analysis and interpretation of the EFA soil function data indicate the combination of root growth and leaf litter deposition contributed to statistically significant ($P < 0.005$) increases in soil function scores by MY-5 (Fig. 28.10).

Vegetation function scores from the same monitoring transects have remained relatively stable over the first five years of monitoring (Fig. 28.11A–C), so the significant increase in the cumulative EFA score (Fig. 28.11D) was driven by the three soil-related functions.

Many of the tree species planted had moderate (2) or high (3) cultural value rankings (Table 28.2), so the Cultural Plant function score started off relatively high and has remained stable (Figs. 28.11A and 28.12A). Similarly, the relatively high number of native tree species planted in 2016 provided an immediate boost in the Forest Succession function score (Fig. 28.11B). Although several individual planted/seeded trees have died since 2016, tree species richness and abundance values have remained stable through natural recruitment of new seedlings (Fig. 28.12B and Table 28.2). Incremental increases in 'non-tree life forms' (e.g., herbs, vines, etc.) have also been observed in these swales. Conversely, other attributes such as 'percent abundance and richness of non-planted native tree species' remain low and apparently will require more than five years for measurable natural recruitment of non-planted species to occur (Fig. 28.12B).

Of the three vegetation functions, the Forest Structural Complexity function has been the most dynamic in terms of attribute value shifts over the first 5 years of monitoring. For example, two variables, 'variation in the mean tree height' and 'variation in mean stem diameter', increased incrementally between MY-1 and MY-3, but by MY-5 these attribute scores declined (Fig. 28.12C) due to mortality of different size trees recorded along some transects. Mortality of some species (e.g., *Casuarina* spp., *Acacia* spp.) may be related to shallow


FIGURE 28.9 Photographs showing groundcover transition from woodchips (MY-1, left), to leaf litter in MY-3 (centre) and combination of leaf litter and plant basal area in MY-5 (right).

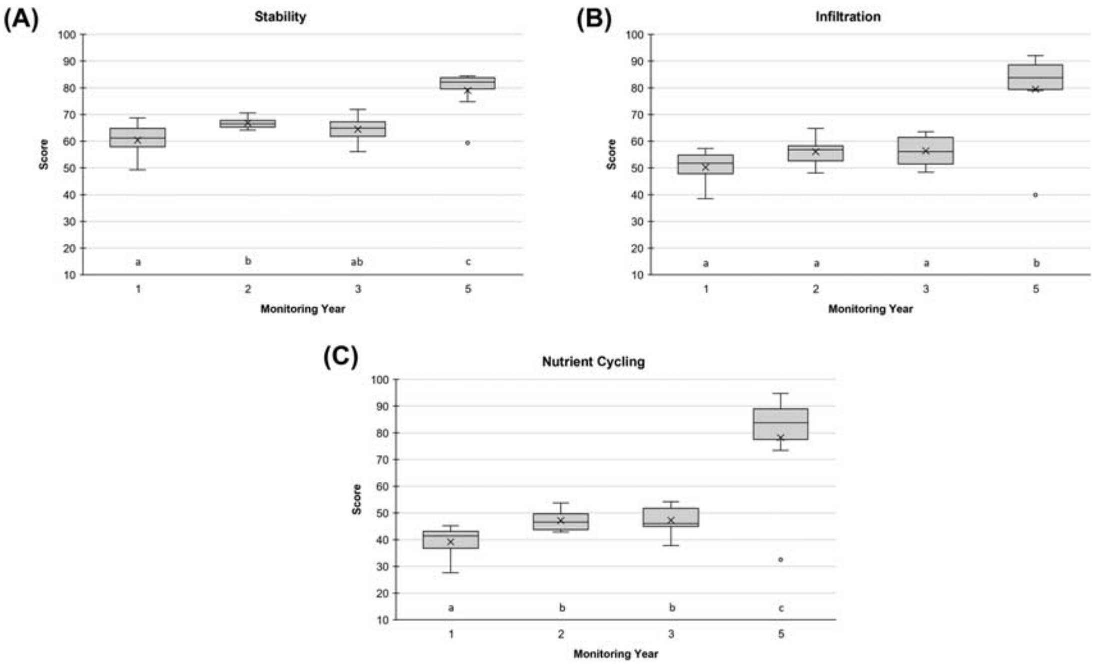


FIGURE 28.10 Score trends for EFA soil functions measured along eight long-term monitoring transects established along slopes of the West Bank stockpile (site WB Swale 2016, n = 8). Letters below boxplots denote statistical similarity or differences ($P < 0.005$) based on a permutation test of independence and post hoc pairwise permutation tests (R Core Team, 2020).

(<50 cm) groundwater and high surface soil moisture content (Table 28.3). However, these moist soil conditions are also facilitating the progressive establishment of hydrophilic herbaceous plant species (i.e., 'non-tree life forms', see Fig. 28.12B. Fig. 28.13), including sedges (*Carex* spp), cattail (*Typha* sp.) and sugar cane (*Saccharum officinarum*). Moist soils and dense herbaceous plant cover are predictably influencing surface soil development and EFA soil function scores (e.g., Nutrient Cycling Function, Fig. 28.10C) but has no influence on the Forest Structural Complexity Function score, which is influenced solely by tree growth-related attributes (Fig. 28.12C).

## Soil analysis

Soil sampling and testing for key physical, chemical and agronomic parameters has been performed since 2017 (though not consistently every year) on various transects located at rehabilitation areas on the East Bank and West Bank stockpiles, within the 1998 revegetation trial area (East Bank Reference) and within a nearby natural tropical forest (KK Reference). Comparison of the monitoring data indicates several differences. Table 28.3 shows that total organic carbon (TOC), total Kjeldhal Nitrogen (TKN) and moisture contents are highest at the KK Reference, intermediate at the East-Bank Reference and West-Bank side-slopes and lowest at the East-Bank top areas. Whereas, pH values are lowest at the KK Reference site (4.4),

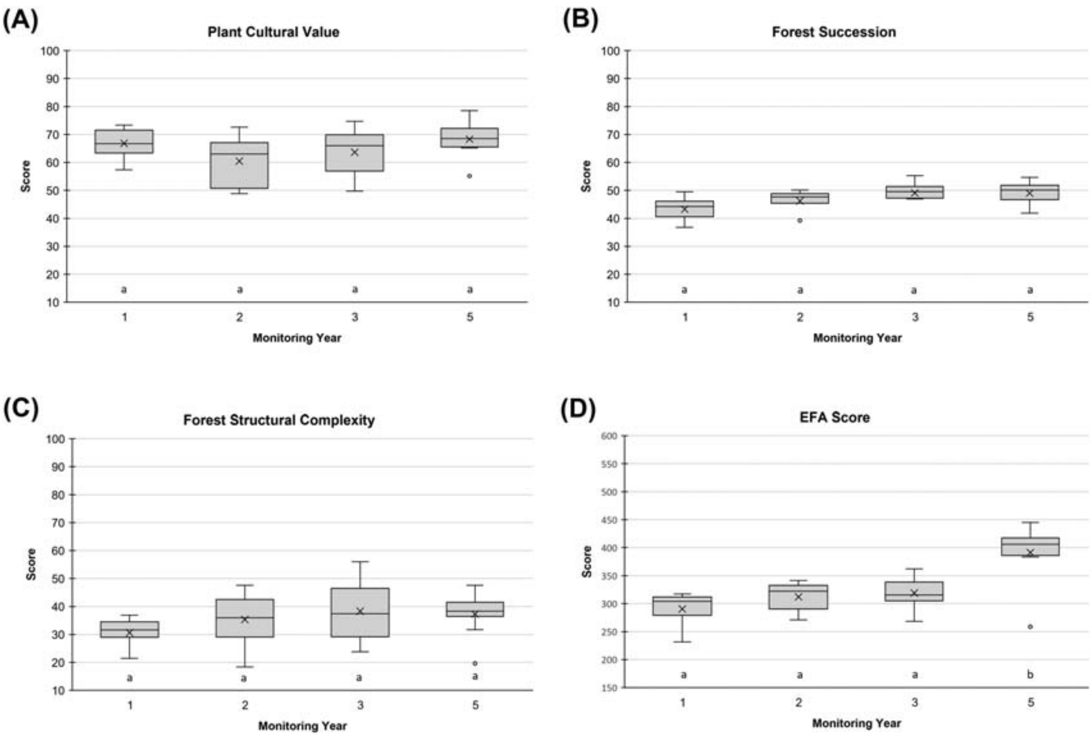


FIGURE 28.11 Score trends for EFA vegetation functions measured along eight long-term monitoring transects established along lower slopes of the West-Bank stockpile (site WB Swale 2016, n = 8). Total EFA score (D) combines function scores from all six EFA functions. Letters below boxplots denote statistical similarty or differences ($P < 0.005$) based on a permutation test of independence and post hoc pairwise permutation tests (R Core Team, 2020).

intermediate at the East Bank Reference (6.1) and highest at the West Bank (8.1) and East Bank areas (8.6). Data from the EB Reference area revegetated in 1998 indicate that pH of the sand tailings have been decreasing over time since rehabilitation. In addition, there are distinct differences indicated at sampling depth at of the monitored sites. In particular, pH is lower and TOC, TKN and moisture content values are higher in the surface samples compared to the deeper samples. This indicates that organic matter accumulations near the ground surface are eventually decreasing surface soil pH and increasing plant nutrient availability over time.

Of note, transects at the West-Bank and the East-Bank Reference areas are located along the base of the stockpile side-slopes; soil sample auger holes typically encountered groundwater at approximately 50–100 cm below ground surface compared to the East-Bank transects, which are located on stockpile top-surface where auger holes did not encounter water and depth to groundwater is much greater. Shallow groundwater availability most likely has a significant effect on the soil development in these areas.

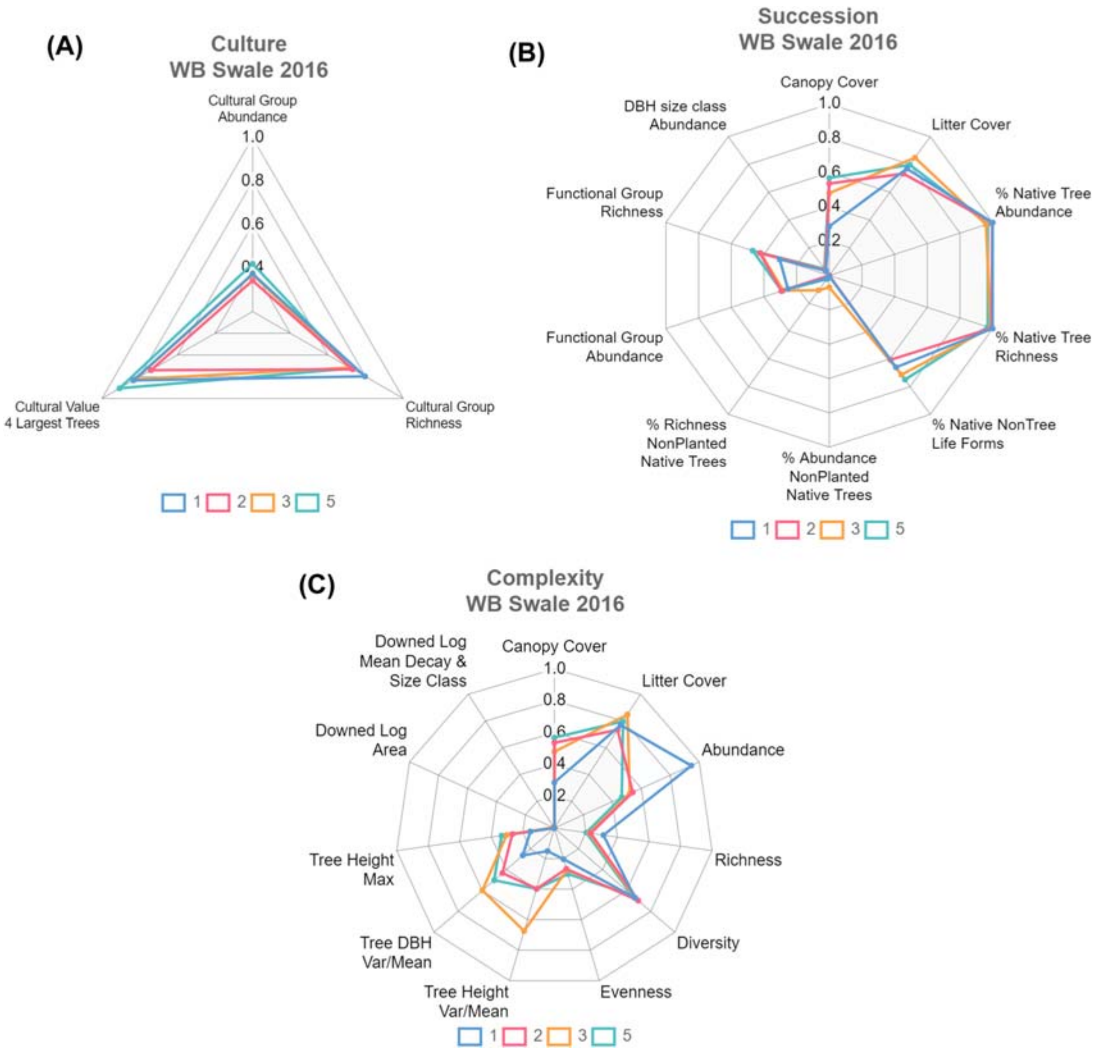


FIGURE 28.12 Score for individual attributes associated with cultural value (A), forest succession (B) and forest structural complexity (C) during the first 5-year monitoring period.

## Adaptive management of the initial rehabilitation

After 5 years implementing the EFA monitoring programme, several initial adaptive management (AM) needs and site development trends have been identified.

- Non-native *Piper aduncum* seedlings are aggressively encroaching onto some newly planted portions of the stockpile. *P. aduncum* is a notoriously successful invasive tree in PNG capable of suppressing pioneer forest species (Leps et al., 2002; Rogers and Hartemink, 2000).

TABLE 28.3 Average concentrations of key soil parameters from samples collected at 0–10 cm and 10–30 cm below ground surface (bgs) along monitoring transects from the East- and West-Bank stockpiles, KK Reference and East Bank Reference areas.

| | | **Total metals** | | **DTPA extractable metals** | | | **Moisture content and nutrients** | | |
|---|---|---|---|---|---|---|---|---|---|
| **Sample depth (cm bgs)** | **Paste pH** | **Copper** | **Zinc** | **Copper** | **Iron** | **Zinc** | **Moisture content** | **Total Kjeldahl nitrogen (as N)** | **Total organic carbon** |
| Unit | Unitless | mg/kg | mg/kg | mg/kg | mg/kg | mg/kg | Percent | mg/kg | Percent |
| ***East Bank stockpile top surface (1-year post rehabilitation)*** | | | | | | | | | |
| 0–10 | 8.6 | 657 | 203 | 40.4 | 17.9 | 5.7 | 6.7 | 52.7 | <0.5 |
| 10–30 | 8.7 | 611 | 193 | 30.1 | 21.2 | 3.8 | 6.1 | 45.3 | <0.5 |
| ***West Bank stockpile slope (5-years post-rehabilitation)*** | | | | | | | | | |
| 0–10 | 8.1 | 519 | 171 | 47.5 | 41.9 | 13.1 | 18.8 | 368 | 1.3 |
| 10–30 | 8.4 | 500 | 185 | 29.1 | 22.2 | 11.5 | 15.2 | 133 | <0.5 |
| ***East Bank reference site (1998 rehabilitation trial area)*** | | | | | | | | | |
| 0–10 | 6.1 | 821 | 175 | 111 | 281 | 10.6 | 18.1 | 890 | 1.4 |
| 10–30 | 7.5 | 1023 | 200 | 51.0 | 23.8 | 4.7 | 11.9 | 183 | <0.5 |
| ***KK reference site (adjacent natural rainforest)*** | | | | | | | | | |
| 0–10 | 4.4 | 55.7 | 57.5 | 1.9 | 199 | 1.2 | 44.8 | 2635 | 4.6 |
| 10–30 | 4.8 | 59.2 | 57.5 | 1.0 | 51.0 | 1.0 | 38.7 | 1485 | 1.8 |

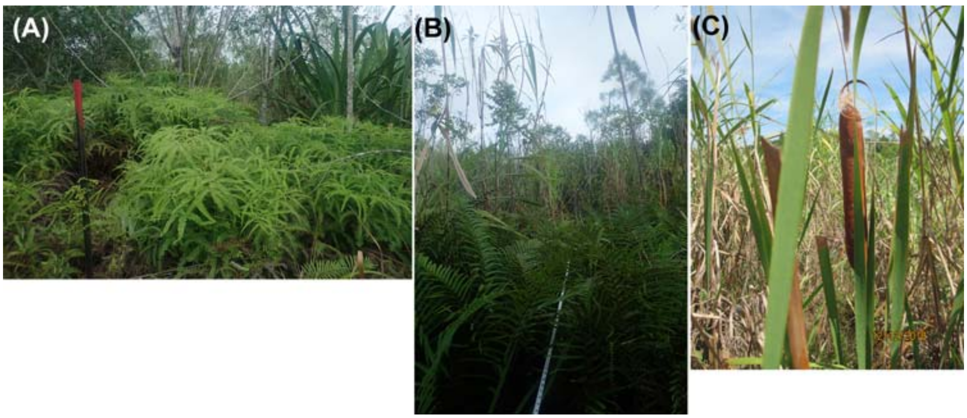


FIGURE 28.13 Representative photographs of natural establishment and growth of herbaceous vegetation in moist soils of the west-bank swales.

AM actions for controlling *P. aduncum* to date include uprooting seedlings with shovels but more intensive, routine searches across the stockpile and broader control strategies need to be developed and implemented.

- Additional monitoring beyond EFA is required to evaluate survival rates of different planted species. Several pioneer species are experiencing high mortality rates, while others are observed growing rapidly and reproducing. Results of this monitoring are needed to refine greenhouse propagation and planting strategies.
- Organic ground cover material (e.g., woodchips) are in short supply and additional material sources and types need to be identified and produced to protect stockpile slopes from rill and gully erosion in the first 1—3 years of rehabilitation.
- Some species (e.g., *Acacia auriculiformis*) produce high volumes of leaf litter that promote plant nutrient availability (Ngoran et al., 2006), soil development, and corresponding EFA function scores. Planting strategies should prioritise Acacia and other broadleaf pioneer species during initial afforestation efforts.
- Seeding methods should be refined to increase establishment rates and survival of seeded species, particularly on the flat top surfaces of the stockpiles.
- Data from the WB Swale 2016 monitoring transects indicate that rehabilitation methods implemented at this site along with natural establishment by ferns and other native herbaceous species are facilitating desired soil functional processes and trajectories within 5 years following initial implementation.
- Monitoring results from the Ok Tedi stockpiles indicate that significant improvement in vegetation-related functions indicative of a resilient forest ecosystem will take longer than 5 years following methods employed across the WB Swale 2016 site.

In addition to field-based AM actions, OTML recognises the importance of periodically re-evaluating assumptions associated with EFA vegetation functions. This includes evaluating the need for adjusting expectations of slope and trajectory of the functions over the 15-to-20-year monitoring period, as well as the appropriateness of certain individual attributes. For example, it is understood that the decomposition of large logs by ants plays an important role in nutrient cycling in moist-tropical forests (Wilson, 1959), and for this reason presence, abundance, size and decomposition stage of logs on the forest floor were included in the *Forest Structural Complexity* function. However, it may be unrealistic to expect log decomposition to contribute much to nutrient cycling over the 15- to-20-year life of the monitoring programme. Such evaluations and adjustments of success criteria are essential in the adaptive management of novel ecosystems (Hulvey et al., 2013; Suding and Gross, 2006; Zedler et al., 2012).

## Application to other novel social—ecological systems

Despite some unique aspects of this Ok Tedi case study, there are several lessons that may be useful to others striving to integrate resilience principles into the rehabilitation of novel ecosystems. First, we found that identifying linkages between ecological and social—cultural resilience early in the planning process has been integral to developing both the rehabilitation framework and the procedures for measuring success. For example, OTML understood at the outset that local communities will depend upon the rehabilitated area to meet their subsistence needs, and if the forest rehabilitation lacks species of cultural value, there is strong risk that they may convert the landscape to accommodate uses that no longer affords the surface protection required to mitigate potential acid-rock drainage into the Ok Tedi. This recognition led to ethnobotanical studies, the integration of culturally important plant species into the rehabilitation programme, the development of quantitative success criteria tied to measuring cultural use values and an adaptive management process to ensure follow through and accountability by OTML. We suggest these process-oriented steps are replicable regardless of where landscape rehabilitation takes place.

Second, reviews of scientific literature indicate a dearth of published case studies addressing development and trajectories of ecosystem functions associated with novel ecosystem rehabilitation. We suggest the 'no-analog' functional trajectory monitoring framework adopted by OTML could be applied and tested across a broad variety of novel ecosystems. This is essentially a learning by doing approach, which has been advocated for novel ecosystems (cf McLoughlin et al., 2020). We acknowledge the monitoring and scoring procedures can always be improved, but such improvements will only be realised through replication, adaptive management, thorough documentation and sharing information through an open peer-reviewed process. It is our hope that more attention will be given to filling this gap in the published literature.

Lastly, applying resilience principles such as ecosystem functional trajectories and integrating traditional knowledge into rehabilitation planning is important, but equally important is ensuring a shared understanding of these principles and programme success criteria among the various entities responsible for programme implementation (i.e., *interactional resilience*, see Chapter 17). Many government agencies and corporations task different groups within their organisations for planning, implementing and monitoring ecosystem rehabilitation programs. Ensuring close communication, collaboration and a shared vision exists between these groups requires strong leadership and governance without which resilience practice runs great risk of falling short of otherwise achievable success.

## References

Arroyo-Rodríguez, V., Melo, F.P., Martínez-Ramos, M., Bongers, F., Chazdon, R.L., Meave, J.A., Norden, N., Santos, B.A., Leal, I.R., Tabarelli, M., 2017. Multiple successional pathways in human-modified tropical landscapes: new insights from forest succession, forest fragmentation and landscape ecology research. Biological Reviews 92 (1), 326—340.

Banks, G., 2001. Papua New Guinea Baseline Study. International Institute for Environment and Development.

Banks, G., 2008. Understanding "resource" conflicts in Papua New Guinea. Asia Pacific Viewpoint 49 (1), 23—34.

Berkes, F., Folke, C. (Eds.), 1998. Linking Social and Ecological Systems: Management Practices and Social Mechanisms for Building Resilience. Cambridge University Press, Cambridge.

BioTropica, 2009. Rehabilitation of Bige Stockpiles: Technical Note 1. Prepared for NRA Environmental Consultants by BioTropica Australia Pty Ltd. March 2009.

Bolton, B.R. (Ed.), 2009. The Fly River, Papua New Guinea: Environmental Studies in an Impacted Tropical River System. Elsevier.

Bridgewater, P., Yung, L., 2013. The policy context: building laws and rules that embrace novelty. In: Hobbs, R.J., Higgs, E.S., Hall, C.M. (Eds.), Novel Ecosystems: Intervening in the New Ecological World Order. John Wiley and Sons, Chichester, UK, pp. 272—283.

Butler, A.R., Toh, I., Wagambie, D., 2012. The integration of indigenous knowledge into mine site rehabilitation and closure planning at Ok Tedi, Papua New Guinea. In: Fourie, A.B., Tibbett, M. (Eds.), Mine Closure 2012: Proceedings of the Seventh International Conference on Mine Closure. Australian Centre for Geomechanics, Perth, pp. 611–626. https://doi.org/10.36487/ACG_rep/1208_52_Butler.

Chapin, F.S., Starfield, A.M., 1997. Time lags and novel ecosystems in response to transient climatic change in arctic Alaska. Climatic Change 35 (4), 449–461.

Chapin III, F.S., Kofinas, G.P., Folke, C. (Eds.), 2009. Principles of Ecosystem Stewardship: Resilience-Based Natural Resource Management in a Changing World. Springer Science and Business Media.

Chazdon, R.L., Finegan, B., Capers, R.S., Salgado-Negret, B., Casanoves, F., Boukili, V., Norden, N., 2010. Composition and dynamics of functional groups of trees during tropical forest succession in northeastern Costa Rica. Biotropica 42 (1), 31–40.

Choi, Y.D., 2007. Restoration ecology to the future: a call for new paradigm. Restoration Ecology 15 (2), 351–353.

Curtin, C.G., Parker, J.P., 2014. Foundations of resilience thinking. Conservation Biology 28 (4), 912–923.

Davies, H.L., Howell, W.J.S., Fardon, R.S.H., Carter, R.J., Bumstead, E.D., 1978. History of the Ok Tedi porphyry copper prospect, Papua New Guinea; I, the years 1966 to 1976; II, the years 1975 to 1978. Economic Geology 73 (5), 796–809.

Doley, D., Audet, P., Mulligan, D.R., 2012. Examining the Australian context for post-mined land rehabilitation: reconciling a paradigm for the development of natural and novel ecosystems among post-disturbance landscapes. Agriculture, Ecosystems & Environment 163, 85–93.

Doley, D., Audet, P., 2013. Adopting novel ecosystems as suitable rehabilitation alternatives for former mine sites. Ecological Processes 2 (1), 1–11.

Dove, J., Miriung, T., Togolo, M., 1974. Mining bitterness. In: Sack, P. (Ed.), Problem of Choice: Land in Papua New Guinea's Future. ANU Press and Robert Brown and Associates, Canberra and Port MOresby, pp. 181–189.

Eberhard, D.M., Simons, G.F., Fennig, C.D. (Eds.), 2021. Ethnologue: Languages of the World, Twenty-fourth ed. SIL International, Dallas, Texas. Online version: http://www.ethnologue.com.

EGi, 2006. Mine Waste and Tailings Project – Sulphide Recovery and Pyrite Concentrate Management. A letter report prepared for Ok Tedi Mining Limited. May 2006.

EGi, 2007. Rationale for Cover Depth on Bige Stockpiles. A Memo Report Prepared for Ok Tedi Mining Limited by Dr Stuart Miller. February 2007.

Eyre, T.J., Kelly, A.L., Neldner, V.J., Wilson, B.A., Ferguson, D.J., Laidlaw, M.J., Franks, A.J., 2015. BioCondition: A Condition Assessment Framework for Terrestrial Biodiversity in Queensland, Assessment Manual Version 2.2. Queensland Herbarium, Department of Science. *Information Technology, Innovation and Arts*, Brisbane.

Filer, C., 1990. The Bougainville rebellion, the mining industry and the process of social disintegration in Papua New Guinea. Canberra Anthropology 13 (1), 1–39.

Folke, C., Carpenter, S.R., Walker, B., Scheffer, M., Chapin, T., Rockström, J., 2010. Resilience thinking: integrating resilience, adaptability and transformability. Ecology and Society 15 (4).

Folke, C., Carpenter, S., Walker, B., Scheffer, M., Elmqvist, T., Gunderson, L., Holling, C.S., 2004. Regime shifts, resilience, and biodiversity in ecosystem management. Annual Review of Ecology, Evolution, and Systematics 557–581.

Gann, G.D., McDonald, T., Walder, B., Aronson, J., Nelson, C.R., Jonson, J., Hallett, J.G., Eisenberg, C., Guariguata, M.R., Liu, J., Hua, F., Echeverria, C., Gonzales, E., Shaw, N., Decleer, K., Dixon, K.W., 2019. International principles and standards for the practice of ecological restoration. Restoration Ecology 27 (S1), S1–S46.

Goosem, S., Tucker, N., 1995. Repairing the Rainforest: Theory and Practice of Rainforest Re-establishment in North Queensland"s Wet Tropics. Wet Tropics Management Authority, Cairns, Australia.

Griffin, J., Nelson, H.N., Firth, S., 1979. Papua New Guinea: A Political History. Heinmann Educational Australia. Pty Ltd.

Griffin, J., 1990. Bougainville is a special case. In: May, R., Spriggs, M. (Eds.), The Bougainville Crisis. Crawford House Press, Bathhurst, pp. 1–15.

GSA, 2013. Bige Rehabilitation Strategy Third Party Review: Final Summary of Findings. Prepared for Ok Tedi Mining Limited by GeoSystems Analysis, Inc., Tucson, Arizona. August 2013.

GSA, 2019. Ecosystem Function Analysis: A Long-Term Monitoring Program for Evaluating Dredged Sand-Stockpile Rehabilitation Success in Bige, Western Province, Papua New Guinea. Prepared by GeoSystems Analysis, Inc., Albuquerque, New Mexico, USA. Amended September 2019. Contract No. OTML 2222176.

GSA, 2021. 2020 Ecosystem Function Analysis Monitoring Results Summary. Prepared for Ok Tedi Mining Limited, Albuquerque, New Mexico, USA. Contract No. OTML CW2234063. September 2021.

Gibson, C.W.D., Brown, V.K., 1985. Plant succession: theory and applications. Progress in Physical Geography 9 (4), 473–493.

Griffiths, J.S., Hutchinson, J.N., Brunsden, D., Petley, D.J., Fookes, P.G., 2004. The reactivation of a landslide during the construction of the Ok Ma tailings dam, Papua New Guinea. The Quarterly Journal of Engineering Geology and Hydrogeology 37 (3), 173–186.

Gunderson, L.H., Allen, C.R., Holling, C.S. (Eds.), 2012. Foundations of Ecological Resilience. Island Press.

Gwenzi, W., 2021. Rethinking restoration indicators and end-points for post-mining landscapes in light of novel ecosystems. Geoderma 387, 114944.

Harantová, L., Mudrák, O., Kohout, P., Elhottová, D., Frouz, J., Baldrian, P., 2017. Development of microbial community during primary succession in areas degraded by mining activities. Land Degradation & Development 28 (8), 2574–2584.

Hettler, J., Irion, G., Lehmann, B., 1997. Environmental impact of mining waste disposal on a tropical lowland river system: a case study on the Ok Tedi Mine, Papua New Guinea. Mineralium Deposita 32 (3), 280–291.

Hobbs, R.J., Arico, S., Aronson, J., Baron, J.S., Bridgewater, P., Cramer, V.A., Epstein, P.R., Ewel, J.J., Klink, C.A., Lugo, A.E., Norton, D., 2006. Novel ecosystems: theoretical and management aspects of the new ecological world order. Global Ecology and Biogeography 15 (1), 1–7.

Hobbs, R.J., Higgs, E., Harris, J.A., 2009. Novel ecosystems: implications for conservation and restoration. Trends in Ecology & Evolution 24 (11), 599–605.

Holling, C.S., 1973. Resilience and stability of ecological systems. Annual Review of Ecology and Systematics 1–23.

Hughes, F.M., Stroh, P.A., Adams, W.M., Kirby, K.J., Mountford, J.O., Warrington, S., 2011. Monitoring and evaluating large-scale,'open-ended'habitat creation projects: a journey rather than a destination. Journal for Nature Conservation 19, 245–253.

Hulvey, K.B., Standish, R.J., Hallett, L.M., Starzomski, B.M., Murphy, S.D., Nelson, C.R., Gardener, M.R., Kennedy, P.L., Seastedt, T.R., Suding, K.N., 2013. Incorporating novel ecosystems into management frameworks. In: Hobbs, R.J., Higgs, E.S., Hall, C.M. (Eds.), Novel Ecosystems: Intervening in the New Ecological World Order, first ed. John Wiley and Sons, Ltd.

Humphries, R.N., 2015. Use of reference sites in the evaluation of some rehabilitated native forests on surface mines in Australia. Journal of the American Society of Mining and Reclamation 4, 36–54.

Jorgensen, D., 2006. Hinterland history: the Ok Tedi mine and its cultural consequences in Telefolmin. The Contemporary Pacific 18 (2), 233–263.

Kanowski, J., Catterall, C.P., Freebody, K., Harrison, D.A., 2008. Monitoring Revegetation Projects in Rainforest Landscapes: Toolkit Version 2, Report to the Marine and Tropical Sciences Research Facility. Reef and Rainforest Research Centre Limited, Cairns.

KCB, 2006a. Mine Waste and Tailings Project: Tailings Storage Study, Updated Draft Report. Prepared for Ok Tedi Mining Ltd by Klohn Crippen Berger. January 2006.

KCB, 2006b. Mine Waste and Tailings Project, Disposal of Pyrite Concentrate at the Dredged Sand Storage Site on the West Bank of the Lower Ok Tedi. Preliminary Report (DCB Report Number M09135A15). May 2006.

KCB, 2014. Lower Ok Tedi Dredge Project: DRAFT East Bank Stockpile Design Update. Prepared by Klohn Crippen Berger for Ok Tedi Mining Limited. May 2014.

Lamb, D., Gilmour, D., 2003. Rehabilitation and Restoration of Degraded Forests.

Lamb, D., Erskine, P.D., Parrotta, J.A., 2005. Restoration of degraded tropical forest landscapes. Science 310 (5754), 1628–1632.

Lepš, J., Novotný, V., Čížek, L., Molem, K., Isua, B., William, B., Kutil, R., Auga, J., Kasbal, M., Manumbor, M., Hiuk, S., 2002. Successful invasion of the neotropical species Piper aduncum in rain forests in Papua New Guinea. Applied Vegetation Science 5 (2), 255–262.

Lindenmayer, D.B., Fischer, J., Felton, A., Crane, M., Michael, D., Macgregor, C., Montague-Drake, R., Manning, A., Hobbs, R.J., 2008. Novel ecosystems resulting from landscape transformation create dilemmas for modern conservation practice. Conservation Letters 1 (3), 129–135.

Lohbeck, M., Poorter, L., Lebrija-Trejos, E., Martínez-Ramos, M., Meave, J.A., Paz, H., Pérez-García, E.A., Romero-Pérez, I.E., Tauro, A., Bongers, F., 2013. Successional changes in functional composition contrast for dry and wet tropical forest. Ecology 94 (6), 1211–1216.

LRS Environmental, 2007. An Assessment of Vegetative Performance on the East Bank Stockpiles and a Discussion of the Future Vegetative Establishment at Bige. Prepared for Ok Tedi Mining Ltd by Land Reclamation Services Pty Ltd. January 2007.

Marshall, A., Marshall, S., 2021. Lower Ok Tedi, Upper Fly and Middle Fly Metroxylon Sagu (Sago Palm) Mapping. Preliminary Results. Prepared For Ok Tedi Mining Limited Environment Department.

McElhinny, C., Gibbons, P., Brack, C., Bauhus, J., 2005. Forest and woodland stand structural complexity: its definition and measurement. Forest Ecology and Management 218, 1–24.

McLoughlin, C.A., Thoms, M.C., Parsons, M., 2020. Reflexive learning in adaptive management: a case study of environmental water management in the Murray Darling Basin, Australia. River Research and Applications 36 (4), 681–694.

Morse, N.B., Pellissier, P.A., Cianciola, E.N., Brereton, R.L., Sullivan, M.M., Shonka, N.K., Wheeler, T.B., McDowell, W.H., 2014. Novel ecosystems in the Anthropocene: a revision of the novel ecosystem concept for pragmatic applications. Ecology and Society 19 (2).

Neldner, V.J., Ngugi, M.R., 2014. Application of the BioCondition assessment framework to mine vegetation rehabilitation. Ecological Management and Restoration 15 (2), 158–161.

Ngoran, A., Zakra, N., Ballo, K., Kouamé, C., Zapata, F., Hofman, G., Van Cleemput, O., 2006. Litter decomposition of *Acacia auriculiformis* Cunn. Ex Benth. and Acacia mangium Willd. under coconut trees on quaternary sandy soils in Ivory Coast. Biology and Fertility of Soils 43 (1), 102–106.

NRA, 2009. Development of Bige Revegetation Program and Completion Criteria. Prepared for Ok Tedi Mining Ltd by NRA Environmental Consultants. November 2009.

NRA, 2011. Incorporating Indigenous Knowledge into Rehabilitation Planning at Ok Tedi Mining Ltd Bige Operations: East Bank Communities. Prepared for Ok Tedi Mining Ltd by NRA Environmental Consultants. November 2011.

NRA, 2012. Review of Native Seed Storage Best Practice for Ok Tedi Mining Ltd. Prepared for Ok Tedi Mining Ltd. By NRA Environmental Consultants. March 2012.

Oates, C.A., 2012. What Price Paradise: A Study of the Effects of the Ok Tedi Mine on Ninggirum People of Papua New Guinea. University of Western Sydney. December 2012.

Oliver, I., Eldridge, D.J., Nadolny, C., Martin, W.K., 2014. What do site condition multi-metrics tell us about species biodiversity? Ecological Indicators 38, 262–271.

Oliver, T.H., Heard, M.S., Isaac, N.J.B., Roy, D.B., Procter, D., Eigenbrod, F., Freckleton, R., Hector, A., Orme, C.D.L., Petchey, O.L., Proença, V., Raffaelli, D., Suttle, K.B., Mace, G.M., Martín-López, B., Woodcock, B.A., Bullock, J.M., 2015. Biodiversity and resilience of ecosystem functions. Trends in Ecology & Evolution 30 (11), 673–684. https://doi.org/10.1016/j.tree.2015.08.009 Available at https://centaur.reading.ac.uk/47800/. ISSN 0169-5347.

OTML, 2007. Bige Closure Plan. Report ENV070625. prepared by the OTML Environment Department.

OTML, 2009. Mine Area Rehabilitation Plan. Report: ENV091126. Ok Tedi Environment Department.

Perring, M.P., Standish, R.J., Hobbs, R.J., 2013. Incorporating novelty and novel ecosystems into restoration planning and practice in the 21st century. Ecological Processes 2 (1), 1–8.

Pickup, G., 2001. Geomorphic Processes in the Ok Tedi and Fly River System: Current Status, Future Trends and Rehabilitation. Report to Ok Tedi Mining Ltd.

Pickup, G., Cui, Y., 2008. Modeling the impact of tailings and waste rock disposal on the Fly River system. Developments in Earth and Environmental Sciences 9, 257–289.

Pickup, G., Marshall, A.R., 2009. Geomorphology, hydrology, and climate of the fly river system. Developments in Earth and Environmental Sciences 9, 3–49.

R Core Team, 2020. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/.

Rau, M.T., Reagan, D.P., 2008. Vegetation of the Ok Tedi–Fly River system. Developments in Earth and Environmental Sciences 9, 515–547.

Regan, A., 1998. Current developments in the pacific. Journal of Pacific History 33 (3), 269–285.

Reilly, B., 2008. Ethnic conflict in Papua New Guinea. Asia Pacific Viewpoint 49 (1), 12–22.

Rogers, H.M., Hartemink, A.E., 2000. Soil seed bank and growth rates of an invasive species, Piper aduncum, in the lowlands of Papua New Guinea. Journal of Tropical Ecology 16 (2), 243–251.

Schulze, C.H., Waltert, M., Kessler, P.J., Pitopang, R., Veddeler, D., Mühlenberg, M., Gradstein, S.R., Leuschner, C., Steffan-Dewenter, I., Tscharntke, T., 2004. Biodiversity indicator groups of tropical land-use systems: comparing plants, birds, and insects. Ecological Applications 14 (5), 1321–1333.

Seastedt, T.R., Hobbs, R.J., Suding, K.N., 2008. Management of novel ecosystems: are novel approaches required? Frontiers in Ecology and the Environment 6 (10), 547–553.

Sekhran, N., Miller, S.E., 1996. Papua New Guinea Country Study on Biological Diversity.

Shearman, P.L., Ash, J., Mackey, B., Bryan, J.E., Lokes, B., 2009. Forest conversion and degradation in Papua New Guinea 1972–2002. Biotropica 41 (3), 379–390.

Society for Ecological Restoration International Science and Policy Working Group (SER-ISPWG), 2004. The SER International Primer on Ecological Restoration. Society for Ecological Restoration International, Tucson. www.ser.org.

Suding, K.N., Gross, K.L., 2006. The dynamic nature of ecological systems: multiple states and restoration trajectories. In: Falk, D.A., Palmer, M.A., Zedler, J.B. (Eds.), Foundations of Restoration Ecology. Island Press.

Suding, K.N., Hobbs, R.J., 2009. Threshold models in restoration and conservation: a developing framework. Trends in Ecology and Evolution 5, 271–279.

Tongway, D.J., Hindley, N.L., 2003. Indicators of Ecosystem Rehabilitation Success. Stage Two – Verification of EFA Indicators. Final Report. Prepared for the Australian Centre for Mining Environmental Research, by CSIRO Sustainable Ecosystems in association with Ben Seaborn, CMLR, University of Queensland. July 2003.

Tongway, D.J., Hindley, N.L., 2004. Landscape Function Analysis: Procedures for Monitoring and Assessing Landscapes with Special Reference to Mine Sites and Rangelands. CSIRO Sustainable Ecosystems, Canberra, Australia.

Van Breugel, M., Bongers, F., Martínez-Ramos, M., 2007. Species dynamics during early secondary forest succession: recruitment, mortality and species turnover. Biotropica 39 (5), 610–619.

Walker, B., Salt, D., 2006. Resilience Thinking: Sustaining Ecosystems and People in a Changing World. Island press.

Walker, B., Salt, D., 2012. Resilience Practice: Building Capacity to Absorb Disturbance and Maintain Function. Island Press, Washington.

Williams, S.E., Marsh, H., Winter, J., 2002. Spatial scale, species diversity, and habitat structure: small mammals in Australian tropical rain forest. Ecology 83 (5), 1317–1329.

Wilson, E.O., 1959. Some ecological characteristics of ants in New Guinea rain forests. Ecology 40 (3), 437–447.

Zedler, J.B., Doherty, J.M., Miller, N.A., 2012. Shifting restoration policy to address landscape change, novel ecosystems, and monitoring. Ecology and Society 17 (4).