Bridging local and global knowledges to classify, describe and map ecosystems

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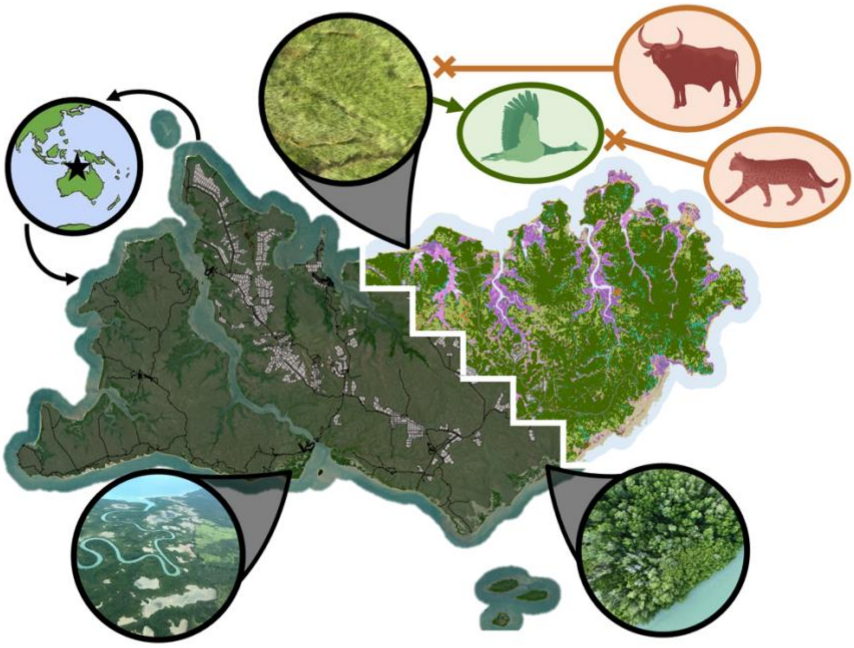
Abstract
Effective ecosystem management for biodiversity and human well-being relies on accurate information. Consistent approaches to classifying, describing, and assessing ecosystems can improve the understanding of the ecological processes, threats, and management. We explored how the Global Ecosystem Typology – a global classification framework based on ecosystem function – could support the development of a local ecosystem inventory for the Tiwi Islands, Australia, to facilitate management by the Indigenous Tiwi peoples and government agencies by incorporating Tiwi knowledge and scientific information. We synthesized ecosystem information from previous research, field data, and reports, together with input from Tiwi knowledge authorities, to develop a classification, descriptions, and map for 14 terrestrial ecosystem types. These ecosystem types were defined and described by ecological processes and were broader, yet largely congruent, with previous classifications. Including functional properties accounted for variation in the vegetation physiognomy exhibited by dynamic and disturbance-prone ecosystems, such as savannas. By bringing together Tiwi knowledge authorities' input, regional information and the Global Ecosystem Typology, we included in our inventory ecosystem types that were typically omitted from previous classifications. Describing the biota within each ecosystem type ensured local relevance and opened new avenues for monitoring, while the Global Ecosystem Typology facilitated comparisons to similar ecosystems in terms of effective threat and management options. Many of the ecosystem types aligned with terms in Tiwi language, significantly enhancing the ways in which global frameworks can support ecological management suitable for Tiwi Country (*murrakapuni*). Beyond this, more collaborative work is needed to explore how the ecosystem inventories and global ecosystem management approaches may operate alongside, and in connection with, the ways of managing Tiwi *murrakapuni* currently enacted by Tiwi people. With the current and ongoing loss of biodiversity, managing ecosystems must span interdisciplinary knowledges and bridge local and global understandings for the shared goal of conservation.

Graphical abstract



Introduction

Maintaining ecosystem integrity is a proactive and cost-effective approach to conservation, sustaining both biodiversity and people (Noss, 1996; Díaz et al., 2018; Nicholson et al., 2021). The management and conservation of ecosystems is predicated upon comprehensive and accurate knowledge of the ecosystem characteristics, drivers and distributions (Wurtzebach & Schultz, 2016). Local information often underpins such ecosystem knowledge. However, ecosystems share traits globally and information could be inferred from similar ecosystems worldwide (Keith et al., 2020). The opportunity and challenge in developing ecosystem knowledge lies in integrating information across scales to leverage the benefits of each (Chaplin-Kramer et al., 2022). Ecosystem information must be fit-for-purpose for local goals and represent the unique assemblages of biodiversity, while also generalisable to and consistent with national and international scales for monitoring and reporting (Convention on Biological Diversity, 2022; Nicholson et al., 2024). Similarly, many fields contribute to ecosystem information, including research domains and institutions, government databases, and Indigenous knowledges. The opportunity and challenge is to bridge knowledge across scales and domains in a consistent and useful manner.

Recent advances in ecosystem science support linking information across scales and domains through consistent approaches to classifying, describing, and assessing ecosystems. In particular, the International Union for Conservation of Nature (IUCN) Global Ecosystem Typology (GET) , an internationally accepted standard for classifying ecosystems (UNSD, 2021; Keith et al., 2022), provides a globally comprehensive typology of ecosystem types within a hierarchical structure of six levels. The higher levels (levels 1 to 3) are defined and described with global relevancy (Keith et al., 2020). The lower levels (levels 5 and 6) emerge from local information such as on-ground observations and plot-based data. The GET defines consistent and ecologically relevant units instrumental for conservation, such as risk assessments, monitoring, planning and valuation (Keith, Ghoraba, et al., 2024; King et al., 2024; Nicholson et al., 2024; Xiao et al., 2024). Here, ‘ecosystem’ refers to a dynamic complex of biotic communities with the abiotic environment interacting as a functional unit, as per the Convention on Biological Diversity (1992). 'Ecosystem types' are differentiated by uniqueness in the composition, structure, processes, and functions (Keith et al., 2020).

Although global consistency has benefits, the ecosystem types must still be relevant to the local scale (Cumming et al., 2006; Schultz et al., 2019), especially for risk assessments, ecosystem accounting, research, and management. Global summaries and broad information can obscure the local context and values, such as threatened and culturally important elements of biodiversity (Turnhout & Boonman-Berson, 2011; Wyborn & Evans, 2021; Goolmeer et al., 2022). These limitations are in part addressed by the lower levels of classification schemes (Hunter & Addicott, 2021; Keith et al., 2022), and harmonising across the available regional classification schemes (Faber-Langendoen et al., In prep.; Lewis et al., In prep.). The GET offers promising opportunities to enhance local ecosystem information and operate at local scales, which are not yet fully explored.

Incorporating cultural values and information of ecosystems from diverse knowledge systems poses a more complex challenge than integrating biodiversity information. In particular, there is a strong need for global frameworks and ecosystem information to recognize the knowledge and aspirations of Indigenous communities (Hill et al., 2021). A range of approaches for bringing together Indigenous and scientific knowledges have emerged over recent decades (Gadgil et al., 1993; Berkes et al., 2000; Raymond et al., 2010; Ens et al., 2015). Co-producing environmental information with on-ground experts can improve scientific findings (Gadgil et al., 1993; Berkes et al., 2000) and better account for the socio-ecological context of decisions (Moorcroft et al., 2012; Harmsworth & Awatere, 2013; Bach et al., 2019). The challenge is maintaining the contextual benefits of global frameworks alongside those of local and Indigenous knowledges (Moorcroft et al., 2012; Tengö et al., 2014).

Here, we present the first application of the GET to develop a local ecosystem inventory while respecting and maintaining local scientific and Indigenous knowledges, through the case study of the Tiwi Islands, in northern Australia. In accordance with ancestral governance practices, Tiwi people undertake strong and active ways of managing Tiwi people-places (*Murrakapuni* in Tiwi language). Within and alongside these practices, biodiversity is managed with contemporary methods and balanced with localized economic development (Woinarski & Baker, 2002). Integrated spatial planning to balance the competing priorities of conservation and development is difficult due to the disparate nature of current data and a lack of fit-for-purpose biodiversity information (Woinarski, 2004). We aimed firstly to apply the GET framework to develop a new local ecosystem inventory that is comprehensive and fit-for-purpose, and that brings together regional and local data with Tiwi perspectives; and secondly, to map the distribution of the ecosystem types to support spatial planning.

Methods

Overview

The research involved multiple steps, many of which interacted with each other (Figure 1). Firstly, we identified and described the ecosystem types of the Tiwi Islands, through an iterative process of reviewing the existing vegetation and ecosystem classifications and consultation with Tiwi knowledge authorities, and compiling written descriptions, photographs and conceptual models for each ecosystem. Secondly, we compiled available, spatially explicit data and undertook on-ground work to identify example locations of each ecosystem type and create training points. We then operationalized the ecosystem inventory with the training points into a predicted map of the ecosystem extent using Landsat-9 satellite imagery and environmental variables in a random forest model.

Study location

The Tiwi Islands comprise Melville Island (5,788 km^2) and Bathurst Island (1,693 km^2), and smaller surrounding islands (Figure 2) within one Australian bioregion "Tiwi-Coburg" (DCCEEW, 2021), and one global ecoregion "Arnhem Land tropical savanna" (Olson et al., 2001). The climate is tropical monsoonal (Bureau of Meterology, 2024). The islands hold national and international conservation significance, supporting endemic, migratory and threatened species (EcoSure, 2009; NRETAS, 2008; Woinarski et al., 2000; Woinarski & Baker, 2002). Tiwi people have managed the lands and waters of the Tiwi Islands for millennia. Tiwi people own the Tiwi Islands under the Northern Territory Land Rights Act 1976 which is administered by the Tiwi Land Council. The eight land-owning clans are Jikilaruwu, Malawu, Mantiyupwi, Marrikawuyanga, Munupi, Wulirankuwu, Wurankuwu, and Yimpinari, which share one language called Tiwi. The Land Council granted permission to undertake this research, access the data and do on-ground work.

Developing the ecosystem inventory

We reviewed seven regional and national classification schemes that cover the Tiwi Islands (summarized in Table 1), which represent the primary source of information used for management and planning. Here, 'classification scheme' refers to both hierarchical systems designed to classify the landscape and mapping datasets which employ a classification system. The schemes we reviewed were a territory-wide map (Wilson et al., 1990), with revisions to the classes and mapping (Brocklehurst & Edmeades, 1998; Woinarski, Brennan, et al., 2003), and additional analyses to resolve single ecosystem types or groups of ecosystems (Russell-Smith, 1991; Fensham & Woinarski, 1992; Menkhorst & Woinarski, 1992; Russell-Smith & Bowman, 1992; Fensham, 1993; Wilson & Fensham, 1994). Parts of the Tiwi Islands have been subjected to land units mapping for forestry and agriculture (see Woinarski & Baker, 2002) which were not included due to restricted areas. We compared the ecological processes, vegetation structural formations, and dominant species or genera documented in the descriptions, and the mapped distribution, where available. In this paper, we use 'vegetation structure' to include the vegetation strata, physiognomy, cover and height. For an example of the comparison, the swamp sedge and grassland ecosystems on the Tiwi Islands alternate between grass and sedge cover in dry and wet season, respectively, due to soil moisture and seasonal inundation (Brocklehurst & Edmeades, 1998; Woinarski & Baker, 2002). Similar species assemblages and species with traits that suggest seasonal flooding are described in NT Macrogroup 14 'Northern Australia Tropical Swamp' with the grass Pseudoraphis spinescens, the water chestnut Eleocharis dulcis, and the water lily Nymphaea violacea (Hunter et al., 2022). The comparison involved an iterative process of conversations with managers, botanists, and a literature review of both the Tiwi-specific information and nearby areas.

We inferred the membership of each class per classification scheme to the Ecosystem Function Groups (EFGs, level 3) of the GET (Table 1), by comparing them with the characteristics from Keith et al. (2022). We assessed the similarities between the classes and the EFGs with reference to the ecological processes that drive the ecosystem function and the ecological properties that result from the common processes, such as the vegetation structure and traits. For example, the C4 photosynthetic pathway appears in grasses that experience regular fire. We also checked the applicability of all other classes listed in the classification schemes to ensure the ecosystem inventory was comprehensive.

We determined an initial inventory by comparing across the classification schemes and the GET to identify all possible ecosystem types occurring on the Tiwi Islands. The resulting ecosystem types corresponded to the GET level 6 ‘Subglobal Ecosystem Types’, hereafter referred to as ‘Tiwi Island ecosystem types’. Within the classification schemes and ecosystem-specific information we reviewed, little information existed for entirely aquatic systems on the Tiwi Islands (e.g. streams), and therefore we did not classify the aquatic ecosystems.

Consultation with Tiwi knowledge authorities

To ensure the ecosystem inventory supported the needs and aspirations of the Tiwi Land Council and Tiwi people in supporting planning for Tiwi Country, we sought to iteratively develop the ecosystem classification and information through discussions with Tiwi knowledge authorities and the Tiwi Rangers. The term ‘Country’ refers “the traditional land and sea territories of Australia’s Aboriginal and Torres Strait Islander Peoples” (Woodward et al., 2020) in a holistic and multidimensional manner (Rose, 1996).

The research team undertook six visits to Country with eight Tiwi knowledge holders, two conversation with three Tiwi knowledge holders who were not Rangers in Wurrumiyanga, multiple ad hoc conversations with Tiwi Rangers (Figure 2, A-I), and one workshop with 11 attendees in Wurrumiyanga (Figure 2, J) between 2021 and 2023. Visit to Country are an established methodology for environmental planning on the Tiwi Islands (Hoverman & Ayre, 2012). Human ethics was approved by the University of Melbourne (ID 1955248). Lists of the Tiwi knowledge holders’ names and the conversation dates are available in appendix S1. Different people from the research team were involved on different visits due to interstate travel restrictions due to Covid-19 and availability. This process was enabled through key Tiwi institutions to respect Tiwi governance processes, including the Tiwi Land Council, Tiwi Resources and Clan groups.

The research team engaged with Tiwi knowledge holders in semi-structured conversations regarding the ecosystem names, adjectives and processes. For the Country visits, we used the location of the visit to initiate the conversation. For the conversations, we used large, printed satellite maps. Example guiding questions are available in Appendix S2. We discussed words in Tiwi language to name and describe the ecosystems, using the Tiwi Plants and Animals list of ecosystem names (TLC et al., 2001) as a prompt when needed. We discussed the ecosystem processes, for example fire, and species that occur at the location and in the ecosystem in general. This led to topics of the meaning and significance of the location for the Tiwi knowledge holders. Finally, we discussed impacts that were damaging either the location or the general ecosystem, and changes to the ecosystems that the Tiwi knowledge holders had observed. This series of questions and topics were discussed in a flexible order and style to focus time on topics that the Tiwi knowledge holders wished to discuss.

We checked the meaning and spelling of the names for the ecosystems elicited during the conversations at the workshop which was part of the Tiwi Resources’ Knowledge Database project, in a presentation to the Tiwi Land Council, in multiple presentations to the *Ngawurra Iuwajirri Ngirramini* scientific reference committee, and in conservations with the Tiwi Rangers. During the workshop, we discussed topics similar to those during the Country visits using the photograph, descriptions and printed maps. We also discussed the comprehensiveness of the ecosystem inventory. The conversations in Wurrumiyanga and workshop provided a context to explore Tiwi governance for cross-cultural landscape planning (Kerinaiua et al., in review).

Developing ecosystem descriptions

We synthesized the available information for the ecosystem types into descriptions and cause-and-effect conceptual models of the interacting processes and characteristics, structured according to Red List of Ecosystems guidelines (Keith, Ferrer-Paris, et al., 2024). These addressed the characteristic and diagnostic native biota, the abiotic features and key ecological processes that influence ecosystem distribution or function, and natural variation in these properties. We specified the threatened species, culturally significant species, and ecosystem services to Tiwi people from the literature (primarily, TLC et al., 2001) and from our conversations. Conceptual models visualize the interactions between major ecosystem components. Five categories of ecosystem components specified by the GET are resource drivers, ambient environment, disturbance regimes, biotic interactions, and human activities (Keith et al., 2022). We systematically compiled information from the literature and on-ground observations related to these components. The attributes of these five components that we recorded were fire frequency and severity, topography, soil type and properties (e.g. salinity), moisture gradients and inundation, invasive species, anthropogenic influences, cultural uses and value, and climate change.

Training points

We developed reference points predominantly from existing spatial data, with a point location for an ecosystem or enough information to create a point location. For the full details of the datasets, see appendix S2. We collated all datasets held by the Tiwi Land Council and aligned the classes with the Tiwi Island ecosystem types via the same methods as the cross-reference. The available datasets were from a diverse range of data providers, including development proposals, aerial photographs, and academic and government research. Most resources related directly to one ecosystem, for example, threatened flora surveys in wet rainforests (Liddle et al., 2008), floristics plots and line drawn maps of the treeless plains (Wilson & Fensham, 1994), and invertebrate sampling in rainforests (Andersen et al., 2012; Munkara-Murray, 2022). Exceptions to this was helicopter photographs from a wildlife survey (unpublished data) and from vegetation mapping (Richards et al., 2012). The locations of the visits to Country with the Tiwi knowledge holders were also used as training points for *Melaleuca* swamps, grasslands, salt marsh, mangrove, sand dunes, sandy coastlines, rocky coastlines, treeless plains, Eucalypt open forest savanna, wet rainforests, and dry rainforests.

Some ecosystem types were identified and described in the inventory, but were not possible to be mapped. The eucalypt open forest savanna and the more variable eucalypt and mixed-species savanna are recognized as distinct ecosystem types by the compositional and structural differences likely reflecting moisture and soil properties. It was not possible to distinguish between them in the existing datasets, due to the variable definitions used for the mixed-species communities and variation in canopy cover visible in the aerial photos. Therefore, eucalypt savanna was mapped as one class which represents mosaics of the two ecosystems. The only data available for rocky shorelines was from our visits with Tiwi people which resulted in too few training points for modelling.

We placed training points on a 30 m grid through visual interpretation in QGIS (version 3.22.12) by overlaying the datasets onto recent Sentinel-2 and Landsat-9 images, and thinned the points to a minimum of 100 m apart to minimize spatial autocorrelation (Congalton &

Green, 1993). This resulted in 5, 298 training points for 11 ecosystem types. For the locations of the training points, see appendix S2.

Model variables

For the satellite imagery, we created a cloud-free Landsat-9 composite by using the median of images from January to May 2023 with less than 30% cloud cover and removing the remaining clouds with a QA-pixel mask (Appendix S3). We used the red and near infrared bands to calculate the normalized difference vegetation index (NDVI) which represents vegetation primary productivity.

We compiled additional environmental layers to represent vegetation and landscape topography from Google Earth Engine (Gorelick et al., 2017) through 'rgee' (version 1.1.6.9999) (Aybar et al., 2020). We obtained the elevation data from the Shuttle Radar Topography Mission 5 m Smoothed Digital Elevation Model (Gallant et al., 2009) and created measures of slope and Topographic Position Index using the 'terra' package in R (Hijmans, 2023). The topographic variables represented groundwater availability as run-off, run-on, and recharge areas. We obtained three layers relating to vegetation height and structure which were the height at which 50%, 75% and 95% of the vegetation biomass has been intercepted (Scarth et al., 2023). For more details, see Appendix S4.

We reprojected the variables to a 30 m resolution and the GDA2020 MGA52S coordinate reference system (EPSG: 7852). We tested the covariate correlation using Pearson's correlation coefficient with a 0.7 cut-off and selected between correlated variables through ecological reasoning or testing the covariates individually in a model (Appendix S4). The final variables used in the model were the red and near infrared bands of the satellite image, NDVI, the height of 95% of the biomass, and elevation.

Model building, evaluation and prediction

We developed a supervised random forest model using the 'ranger' package (Wright & Ziegler, 2017) to classify ecosystems and predict their distribution. Random forests are tree-based, machine-learning, ensemble models (Breiman, 2001) common for multi-class classification (Cutler et al., 2007). All analysis was undertaken in R (version 4.3.0) (R Core Team, 2018) with R-studio (version 2023.09.1+949) (RStudio Team, 2020). For all software and packages used, see appendix S5.

We randomly allocated the training points into five partitions for cross-validation. Cross-validation involves assigning each data point into one of *k* partitions, using all but one of the partitions to build a model, and predicting to the held-out partition. This process is repeated so that each partition is held-out once. We optimized the modelling parameters, resulting in 60 trees, 2 splitting variables and 6 nodes deep, and weighted samples by the sample size (Appendix S5). We used the cross-validated models to predict the ecosystem type in the held-out partition and from this, calculated the confusion matrix by assessing true and predicted ecosystem types. We calculated and report on the overall accuracy, the kappa index of agreement and the class-specific accuracy measures from the cross-validated confusion matrix (Appendix S5), noting the limitations of accuracy metrics derived from non-randomly sampled training points and of the kappa statistic (Foody, 2002; Olofsson et al., 2013; Pontius Jr & Millones, 2011). We used the cross-validated models to predict the ecosystem type for the entirety of the islands. The final predicted class was the class predicted most frequently from the cross-validated models or with the mean highest probability where multiple classes were predicted in equal amounts, and overlayed the extent of urban and forestry areas.

Results

The ecosystem inventory

On the Tiwi Islands, we identified 14 ecosystem types (Table 2): 12 native terrestrial and terrestrial-transitional (types 1-12), and two anthropogenic (types 13-14). In terms of the relationships to the IUCN GET, the 12 native ecosystem types (GET level 6) belonged to 10 EFGs (GET level 3), seven biomes (level 2) and four realms (level 1, Table 2). Half the ecosystem types are fully terrestrial (n = 6), and half are transitional with either the marine realm (n = 3), freshwater (n = 1) or both marine and freshwater (n = 2).

The biome and EFG representing the most ecosystem types were the 'T4 savanna and grassland biome' and the 'T4.2 pyric tussock savanna' EFG, respectively, with three ecosystem types: the widespread eucalypt open forest savanna (type 1, *warta*), the patchily distributed eucalypt and mixed-species savanna (type 2, *warta*), and the structurally diverse *Melaleuca* savanna (type 6, *punkaringa*) (Table 2). The eucalypt open forest savanna (type 1, *warta*) was the most widespread ecosystem with a canopy of *Eucalyptus miniata*, *E. tetrodonta*, and *Corymbia nesophila* over a grassy understory which promotes regular fires. The eucalypt and mixed-species savanna (type 2, *warta*) has a heterogeneous floristic species composition with a lower canopy height and cover than the open forest savanna. The *Melaleuca* savanna (type 6, *punkaringa*) occupies a niche exposed to seasonal extremes of water logging and drought. The two eucalypt savanna ecosystem types differ in their dominant species, structural formations and likely fine-scale edaphic factors and drainage. However, all three savanna ecosystems share the importance of fire as a driving ecological process through the presence of grass cover and traits evolved to regular fire, and seasonal water deficit. The next most common biomes were 'T1 tropical-subtropical forests', 'MTF1 brackish tidal' and 'MT1 shorelines' representing two ecosystem types each. The anthropogenic ecosystem types were from the 'T7 intensive land use' and 'MT3 anthropogenic shorelines' biomes (Appendix S8).

Moisture availability is a key characteristic and driver for all the ecosystem types (Figure 3; Appendix S7). Stable freshwater availability drives one ecosystem (the wet rainforest, *kukuni yawurlama* type 4), while a seasonal deficit of freshwater influences six terrestrial ecosystems (types 1-3 and 5-7). Regular salt and brackish water inundation drives mangrove distributions (*mirriparinga* or *pamparinga* type 8). Regular tidal saltwater input is crucial for the sandy and rocky shorelines (*tingata*, types 11 and 12), while irregular inundation is key to the coastal saltmarsh (*yarti*, type 9). Freshwater availability also interacts with fire to distinguish between ecosystem types. For example, fire mediates the boundaries of the wet rainforest and the pyric eucalypt savanna (*warta*); fire is minimal within the rainforest (*yawurlama*) due to the predominantly evergreen vegetation. Fire is also reduced in the dry rainforest (type 5, *yartupwarri yawurlama*) despite the drier vegetation, suggested as due to topographical protection. The dry rainforest is semi-deciduous due to the seasonal drought.

Multiple threats act or have the potential to act on each ecosystem (Figure 3, yellow boxes). The main threats appear to be inappropriate fire regimes, invasive species, climate change, and interactions among these threats. Fire is an important process in the savanna systems and hence changes in fire frequency, severity, or extent would likely cause significant impacts. In this region, fires occur in high frequency at low intensity (Murphy et al., 2013; Williams et al., 2017). An inappropriate fire regime is defined as high severity fires occurring in the late dry season (after July) which can cause large changes to vegetation communities (Fox et al., 2001). In terms of invasive species, exotic perennial pasture grasses common in other regions of northern Australia, such as gamba grass (*Andropogon gayanus*), mission grass (*Cenchrus polystachios*), para grass (*Urochloa mutica*) and olive hymenachne (*Hymenachne amplexicaulis*) have the potential to degrade ecosystems by altering the fire regimes and outcompeting native species (Figure 3, Appendix S7). Feral herbivores, in particular buffalo (*jarranga*, *Bubalus bubalis*) and pig (*pikipiki*, *Sus scrofa*), degrade multiple ecosystems by reducing regeneration in sensitive rainforest, uprooting plants, spreading weeds, and worsening water quality (Figure 3). Feral cats (*Felis catus*) are a growing issue with impacts through predation on mammals, birds and reptiles (H. F. Davies et al., 2017, 2021) (Figure 3). Climate change may increase severe weather events (such as cyclones) and cause sea level rise, exacerbating coastal erosion, which is already a prominent issue for Tiwi people (Barnett et al., 2023).

No single classification scheme previously developed and used in Australia captured all the Tiwi Islands ecosystem types identified in our inventory. The 12 native terrestrial and terrestrial-transitional native ecosystem types for the Tiwi Island from this research were referrable to 10 IVC level 3 formations and 14 NVIS major vegetation groups (Table 2; Appendix S8). Despite differences in the classification criteria and objectives of the global and national classifications, a one-to-one attribution or one-to-many between the schemes was possible for most classes. Ecosystem types were abstracted at a similar thematic scale to the generalised vegetation types previously described for the Tiwi Islands. Existing classifications of vegetation communities (e.g. vegetation types for mangroves) nested into the Tiwi Island ecosystem types. The treeless plains ecosystem type (*muriyini*) did not easily align to a single category in the national and territory classification schemes, although it was recognized in previous classifications specific to the Tiwi Islands. The treeless plains is a shrubland ecosystem type with diverse vegetation, demarcated by Wilson & Fensham (1994) into five distinct vegetation communities. The distribution and floristic variations in the treeless plains ecosystem and similar shrublands in the Northern Territory (NT) are driven by edaphic properties, including type, depth and nutrients, and interactions with soil moisture (Appendix S7, DCCEEW, 2011).

The Global Ecosystem Typology and conversations with Tiwi knowledge holders prompted the inclusion of three unvegetated or sparsely vegetation ecosystem types: sand dunes (type 10, *kurlimipiti* or *pungamparna*), sandy shorelines (type 11, *tingata*) and rocky shorelines (type 12, *tingata*). These unvegetated ecosystems were either not included in previous classification schemes or aggregated into a single class (i.e. class 27 in NVIS). Sandy and rocky shorelines (*tingata*) exist at the transitional zone between the marine and terrestrial realms. Both ecosystems experience tidal inundation, wave action and desiccation which drive the community structure. The difference between the ecosystems lies in the substrate with microtopographic variations in the rocky surface providing refuges from these drivers. Both types of shorelines are used by Tiwi people regularly and provide access to marine and intertidal areas for hunting and fishing. In contrast, sand dunes (*kurlimipiti* or *pungamparna*) exist above the high tide mark. Sparse vegetation grows on the dunes as a matrix of bare sand and *Spinifex longifolius* (*pitarika*). Bernard Tipiloura shared his experience camping near the sand dunes in southeast Bathurst Island when he was young.

Tiwi language

Tiwi knowledge authorities shared words in Tiwi language that appeared to broadly align to the ecosystem types in this research, often with one name in Tiwi per ecosystem (e.g. '*turringiya'* for grasslands and sedgeland wetlands). For rainforests, the Tiwi name '*yawrulama'* was used for both wet and dry rainforests, representing the GET biome 'T1

Tropical-subtropical forests'. However, Tiwi knowledge holders recognized and acknowledged differences between the wet and dry rainforests. Colin Kerinaiua described the difference in the rainforests by species composition and biotic characteristics, while Bernard Tipiloura described the different services provided to Tiwi People (e.g. the collection of yams). Bernard Tipiloura suggested adjectives that could be used to distinguish between these rainforest ecosystems: Tiwi words for freshwater '*kukuni'* and '*kukunila'*, and for freshwater stream '*makaringa'* to describe the wet rainforests, while '*yartupwarri'* meaning dry ground for the dry rainforests (Table 2). It is unclear if these adjectives were used by Tiwi knowledge holders in this instance to approximate the ecosystem types from this research to Tiwi language, or if the adjectives are part of an established Tiwi conceptualisation and description of the landscape.

Ecosystem mapping
Expanses of eucalypt savanna (*warta*) dominates the terrestrial landscape of the Tiwi Islands with patchy areas of treeless plains (*muriyini*) and *Melaleuca* savanna (*punkaringa*), while tracts of mangroves (type 8, *mirriparinga* or *pamparinga*) line the coastline (Figure 4.A). The predictive model achieved a high overall accuracy of 85% and kappa statistic of 83% (Table 3; Appendix S6). Across the ecosystem classes, ocean (*winga*) was consistently predicted with the highest user's and producer's accuracies of 1 and 0.99 respectively (Table 3). In contrast, *Melaleuca* savanna (*punkaringa*) was overpredicted (UA = 0.26). Treeless plains (*muriyini*) were also often misclassified, albeit to a lesser extent, both falsely predicting treeless plains when another ecosystem truly occurred (false positive, UA=0.66) and falsely predicting another ecosystem when treeless plains truly occurred (false negative, PA = 0.7). Similarly, wet rainforests (*kukuni yawurlama*) tended to be overpredicted (UA = 0.64) due to the misclassification of dry rainforests (*yartupwarri yawurlama*, PA = 0.8).

Discussion

In this study, we created a Tiwi Islands ecosystem inventory that brings together local and national information within a global framework. Our results illustrate that a focus on function in defining ecosystem types effectively captures the high spatio-temporal variation in dynamic and disturbance prone ecosystems, such as the pyric savanna. The new inventory captures a greater range of ecosystem types than any other single classification that we reviewed, including separating unvegetated ecosystems into individual classes, and describing ecosystems at the terrestrial-marine interface, which were identified by Tiwi people as important culturally and ecologically. This work illustrates the benefits gained by connecting knowledge systems and scales, including local Indigenous knowledge, and scientific knowledge from local to global scales.

Dynamic savanna ecosystems, such as those that dominate Tiwi islands, are well represented by a classification based in function that emphasises the role of fire as an ecological process and reduces reliance on vegetation structure in classification. Vegetation structure is a core property traditionally used in vegetation classification and mapping but has diminished use for distinguishing ecosystems with spatiotemporally variable structural or floristic forms, such as savannas, which exhibit high spatio-temporal variability in structure (Fox et al., 2001; Parr et al., 2014; Williams et al., 2017). Structural classifications of savannas can produce inaccurate extent estimates and inappropriate management (Ratnam et al., 2011; Griffith et al., 2017; Phelps et al., 2022). On the Tiwi Islands, variation in the eucalypt savanna (*warta*) challenged previous mapping (Woinarski, Brennan, et al., 2003), where slight structural or floristic variation resulted in vegetation types split by canopy cover and composition (Brocklehurst & Edmeades, 1998; Woinarski, Brennan, et al., 2003). In contrast, grouping them as an ecosystem type based on frequent fires, seasonal drought, and biota whose traits are shaped by those ecological processes (Williams et al., 2017), notably signalled by the abundance of seasonally flammable C4 grasses, results in a functional classification that accounts for ecosystem dynamics and variation. Whether defined by vegetation structure or ecosystem processes, savanna variability still challenges mapping (Hanan et al., 2014; Hurskainen et al., 2019) with significant implications for policy and conservation (Dorrough et al., 2021). Some level of uncertainty is unavoidable when demarcating landscape features in a natural continuum.

Drawing on existing classification knowledge enabled the development of a Tiwi Islands ecosystem inventory that was more comprehensive than any of the earlier classifications, and prompted inclusion of locally important ecosystem types. For example, the treeless plains ecosystem (*muriyini*) did not easily align to a class with the national NVIS mvg and NT vegetation map, for multiple potential reasons. Primarily, the national and NT information operate at different thematic scales to the Tiwi Island ecosystem types. NVIS uses broad vegetation types as units, whereas the treeless plains ecosystem encompass multiple vegetation types which vary with subtle ecological gradients (Wilson & Fensham, 1994). Secondly, it is understandable that an ecosystem with a remote and scattered distribution in small patches across the Tiwi Islands (Woinarski & Baker, 2002) and the NT (DCCEEW, 2011) may not be well captured in a nationally relevant product. Similar to the gap in NVIS, the regionally endemic Tiwi wet rainforests are not currently included in the GET indicative maps for EFG 'T1.1. Tropical/Subtropical lowland rainforests', again potentially due to the narrow extent and isolated patches. Such gaps in the national and global information highlight the importance of fit-for-purpose, local scale inventories for ecosystem management.

Contributions from Tiwi knowledge authorities significantly improved the comprehensiveness of the inventory. Together with GET indicative maps, Tiwi people identified three unvegetated and sparsely vegetated ecosystems present on the Tiwi Islands as sand dunes, sandy shorelines, and rocky shorelines. Sand dunes are a prominent landform on Bathurst Island, and provide ecosystem services with scattered medicinal plants (Thompson et al., 2019), access to mangroves for hunting, and as landscapes of cultural stories. Unvegetated and sparsely vegetated ecosystems were often overlooked in classification schemes (Brocklehurst & Edmeades, 1998; Faber-Langendoen et al., 2014), or amalgamated these disparate ecosystem types into a single heterogeneous class (e.g. class 27 and 42 in the case of NVIS mvg and mvsg, respectively). Sparsely vegetated dunes were directly impacted by sand mining, for which there is recurring interest (EcOz Environmental Services, 2012). The addition of unvegetated and sparsely vegetated ecosystems improved the comprehensiveness of the ecosystem inventory. Such complete coverage better supports spatial planning, and the recognition of the values of ecosystems for Tiwi people.

Tiwi knowledge authorities also offered important insights into the classification and description of the ecosystem types. Internationally, Indigenous landscape classification has been explored, albeit to a lesser degree than other aspects of Indigenous knowledge (Berkes et al., 1998; Boillat et al., 2013). The landscape types described by Indigenous groups vary greatly in defining attributes and the contribution of cultural aspects to the definition. Highly nuanced classification by Indigenous groups has been documented by Indigenous peoples of the Peruvian and Bolivian Amazon rainforest (Fleck & Harder, 2000; Shepard Jr et al., 2001; Halme & Bodmer, 2007; Wartmann & Purves, 2018), in Romania (Babai & Molnár, 2013) and Mongolia (Gantuya et al., 2019). These differences represent conceptual distinctions in how the landscape is understood. Words in Tiwi language aligned well with either ecosystem types or with the GET biome (level 2) scale, such as *warta* for the savanna (T4) and *yawurlama* for rainforest (T1), although we acknowledge the ontological differences between these understandings of the landscape. Instead of seeking comparison between the conceptualisations, we aimed to create an ecosystem inventory through collaboration that was fit-for-purpose to manage Tiwi *murrakapuni*. Indigenous and scientific methods to define the landscape are different as they emerge from disparate knowledge systems, yet they should be equally respected (Agrawal, 1995) and may together support effective conservation action. Differences in landscape classification has practical implications. Navigating these differences can facilitate collaboration and better balance conservation and local aspirations (Wartmann & Purves, 2018). Participatory mapping of landscapes with Indigenous peoples can both elucidate the landscape classes and support spatial planning, such as undertaken by the Anindilyakwa people in northern Australia (Davies et al., 2020). Participatory mapping with Tiwi knowledge authorities could be useful to describe the aquatic ecosystems and complement previous collaborative research for water planning (Hoverman & Ayre, 2012) and environmental change (Barnett et al., 2023).

Grounding the ecosystem inventory in function and describing the constituent biota of the system opens new avenues for monitoring and management (e.g. in the IUCN Red list of Ecosystems assessments, (Keith, Ferrer-Paris, et al., 2024). For savannas, low canopy cover or high fire frequency can be misinterpreted as degradation, with reforestation programs or fire suppression wrongly implemented (Parr et al., 2014; Phelps et al., 2022). Instead, monitoring the ecosystem processes, such as fire extent, severity and frequency, or the ecosystem biota, such as threatened mammals and birds for the Tiwi Islands (Davies et al., 2018, 2019, 2021; Stobo-Wilson et al., 2019; MacColl et al., 2023) may better indicate integrity (Parr et al., 2014; Griffith et al., 2017). Biocultural indicators are an emerging method to monitor landscapes by incorporating Indigenous values (Moorcroft et al., 2012; McElwee et al., 2020; Goolmeer et al., 2022). In compiling our inventory, we described the threatened and culturally significant species of each ecosystem. For example, mangroves support whelk populations, which provide food resources for Tiwi people (TLC et al., 2001); grasslands are essential for migratory magpie geese that are hunted (TLC et al., 2001). The inclusion of cultural significance in the ecosystem descriptions was a crucial step in maintaining local relevancy and could underpin monitoring to maintain cultural values.

To conserve and manage ecosystems, we must complement monitoring with tangible actions to minimize threats (Lindenmayer et al., 2013). Threatening processes on the Tiwi Islands include inappropriate fire regimes, feral animals, weeds and vegetation clearing primarily for infrastructure development, as well as the interaction of these processes (Woinarski & Baker, 2002; Woinarski, Hadden, et al., 2003). Through the conceptual models, we established clear pathways to maintain key processes and abate major threats. The ecosystem descriptions and extent map are powerful tools for identifying ecosystems and areas important to conserve for natural and cultural values, as well as the services the ecosystems provide. Meanwhile, the GET and cross-referencing between classification schemes can facilitate knowledge sharing on threats and effective management strategies. Feral buffalo (*Bubalus bubalis*) have damaged floodplains across northern Australia (Bradshaw et al., 2007; Bowman et al., 2010). Although the extent of such impacts on the Tiwi Islands is unknown, management actions could be informed by experiences from Kakadu National Park, including the quantification of buffalo impacts and consultation processes to develop control programs (Bradshaw et al., 2007).

Spatially-explicit management of ecosystems requires distribution maps. A crucial aim of this research was operationalising the ecosystem inventory into an ecosystem map for spatial planning. Our modelling produced high overall accuracy, but low accuracy for specific classes (Table 3). The high overall accuracy is potentially an overestimation due to the random allocation of the training points into the cross-validation folds (Stehman & Foody, 2019) because some validation points will be close to training points and likely have similar characteristics. Low by-class accuracy indicates that some classes are poorly defined within the model. For example, wet and dry rainforests were often mistaken (Table 3). The environmental variables potentially did not capture the functional differences and resulting differences between the rainforest types which were identified in the ecosystem descriptions. Variables which reflect the seasonal soil moisture dynamics or deciduous nature of dry rainforests may improve the predictions. *Melaleuca* savanna was also over-predicted, potentially related to the paucity of training points for the class or the structural variability. Poor accuracy is common for heterogeneous classes (Congalton et al., 2014), opposing the benefit gained by ecosystem units in capturing the structural variability.

In a century defined by biodiversity loss, conservation must mobilize all available knowledge and apply integrated approaches managing the environment holistically. Here, we explored bridging global generalisations and local information for ecosystems. We observed reciprocity between the scales, with the flow of knowledge between the GET and the Tiwi Island information. The GET supported inferences on local ecosystem functioning through global similarities and guided the inventory development with consistency for future applications. Local information and Tiwi knowledge generated a fit-for-purpose inventory relevant to the environmental and social context, and fine-scale distribution maps. However, there were considerable challenges. Future work should examine how an ecosystem inventory could better represent Indigenous knowledges and values, including if and how global frameworks can best support Indigenous people's Country, their knowledge, governance, and aspirations (Reed et al., 2017; Hill et al., 2021). There were strong overarching similarities in the Tiwi Islands ecosystem types with the different classification schemes. Hence, the different knowledge systems can complement and strengthen each other. Bringing together the knowledge across scales into a consistent hierarchical system facilitates understanding the broader context of conservation priorities and management options, and encourages effective action (Chaplin-Kramer et al., 2022).

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Tables

Table 1. The global, national, and regional classification schemes applicable to the Tiwi Islands, Australia which were reviewed and assigned membership to the Global Ecosystem Typology to establish an ecosystem inventory.

Classification scheme	Key scientific references	Spatial scope	Mapped spatial scale	Description
IUCN Global Ecosystem Typology Ecosystem Functional Group (GET EFG, level 3) https://global-ecosystems.org	(Keith et al., 2022)	Global	Varies from 10 minutes to 1 degree	The GET is a unifying conceptual framework to contextualize the ecosystems of the world. The ecosystem classes are defined by their processes and functions in a hierarchical structure. Each type is described with written documentation and indicative global distribution maps. The GET is designed to be globally comprehensive and has been accepted as an international standard to classify ecosystems.
International Vegetation Classification (IVC) system	(Faber-Langendoen et al., 2014, 2018, In prep.)	Global	-	The IVC is an expert-developed global classification of terrestrial vegetation types based on "vegetation criteria, including physiognomy (growth forms, structure) and floristics … with ecological characteristics, including site factors, disturbance, bioclimate, and biogeography".
Northern Territory (NT) macrogroups	(Hunter et al., 2022; Lewis et al., In prep.)	Northern Territory	-	The NT macrogroups are the broad vegetation types for the Northern Territory at an IVC level 5 macrogroup derived from vegetation plot data and species co-occurrence patterns.
Northern Territory (NT) vegetation map	(Wilson et al., 1990)	Northern Territory	1:1 million scale	The NT vegetation map is a regionally consistent vegetation typology and line drawn map from aerial photographs. The classes are based on a structural scheme modified from Specht (1981) with floristic and structural attributes from plot-based data.
Generalised vegetation types of the Tiwi Islands	(Brocklehurst & Edmeades, 1998)	Tiwi Islands	Overall at 1:250,000. Selected areas at 1:100,000	The generalised vegetation types were downscaled from the NT vegetation map classes with floristic inventories using Specht (1970). Fine-scale maps of rainforest using Webb (1968,1978) structural typology and *Melaleuca* forests using Walter and Hopkins (1990) were overlayed.
Tiwi Island vegetation map	(Russell-Smith & Bowman, 1992; Woinarski et al., 2000; Brocklehurst & Lynch, 2009)	Tiwi Islands	30 m	The Tiwi Island vegetation map describes and maps vegetation classes which were derived from grouping unsupervised clusters from a 1995 Landsat-5 satellite image into broad vegetation types. Fine-scale maps of rainforest using Webb (1968,1978) structural typology and *Melaleuca* forests using Walter and Hopkins (1990) were overlayed.
National Vegetation Information System major vegetation groups (NVIS mvg, version 6) National Vegetation Information System major vegetation subgroups (NVIS mvsg, version 6)	(NLWRA, 2001; DCCEEW, 2020)	Australia	100 m	NVIS is a nationally consistent scheme and composite map using vegetation mapping from the Australian States and Territory. In general, the classes were defined and described using "structural and floristic patterns" in the dominant genera. The structural formation employs Specht (1970), Specht *et al.*, (1974) and Walter Hopkins (1990). For the Tiwi Islands, NVIS was largely derived from the Tiwi Island vegetation map (Woinarski et al., 2000).

Table 2. Cross-reference of the Tiwi Islands ecosystem types and associated words in Tiwi language with the Global Ecosystem Typology and two example classification schemes developed for the national and regional scales.

Type ID	Tiwi Island ecosystem type	Words in Tiwi language	GET[a] Ecosystem Functional Group (level 3)	NVIS[b] major vegetation group	Generalised vegetation type	Key scientific literature
Terrestrial or terrestrial-transitional ecosystems						
1	Eucalypt open forest savanna	*Warta*	T4.2 Pyric tussock savanna	3. Eucalypt open forests	1. Eucalyptus forests (4 sub-categories)	(Fox et al., 2001; Woinarski & Baker, 2002; Woinarski, Brennan, et al., 2003; Richards et al., 2012)
2	Eucalypt and mixed species savanna	*Warta*	T4.2 Pyric tussock savanna	12. Tropical eucalypt woodlands/grasslands	1. Eucalyptus forests (4 sub-categories)	(Woinarski & Baker, 2002; Woinarski, Brennan, et al., 2003)
3	Treeless plains	*Muriyini*	T3.1 Seasonally dry tropical shrubland	31. Other open woodlands 17. Other shrublands 16. *Acacia* shrublands 13. *Acacia* open woodlands 6. *Acacia* forests and woodlands	5. Sparsely wooded plains (5 sub-categories)	(Wilson & Bowman, 1994; Wilson & Fensham, 1994; Woinarski & Baker, 2002)
4	Wet rainforest	*Yawurlama* (jungle) *Kukuni* (freshwater) *Makatinga* (stream)	T1.1 Tropical/subtropical lowland rainforest	1. Rainforests and vine thickets	4b. 'Wet' monsoon forests	(Fensham & Woinarski, 1992; Menkhorst & Woinarski, 1992; Russell-Smith, 1991; Russell-Smith & Bowman, 1992)
5	Dry rainforest and vine thickets	*Yawurlama* (jungle) *Yartupwarri* (dry ground)	T1.2 Tropical/subtropical dry forest and thickets	1. Rainforests and vine thickets	4a. Dry monsoon vine thickets	(Russell-Smith, 1991; Russell-Smith & Bowman, 1992)
6	Melaleuca savanna	*Punkaringa*, *Pikaringini* (paperbark)	T4.2 Pyric tussock savanna	9. *Melaleuca* forest and woodland	2. *Melaleuca* forests (2 sub-categories)	(Woinarski, Brennan, et al., 2003; Brocklehurst & Lynch, 2009)
7	Grasslands and sedgeland wetland	*Turringiya*	TF1.4 Seasonal floodplain marshes	21. Other grasslands, herblands, sedgelands and rushlands	6. Swamps, sedgeland	(Woinarski, Brennan, et al., 2003)
8	Mangroves	*Mirriparinga* *Pamparinga*	MFT 1.2 Intertidal forests and shrublands	23. Mangroves	3. Mangroves (7 sub-categories)	(Messel et al., 1979; Brocklehurst & Edmeades, 1998; Woinarski, Brennan, et al., 2003)
9	Coastal saltmarsh	*Yarti*	MFT1.3 Coastal saltmarsh and reed-bed	22. Chenopod shrublands, samphire shrublands and forblands	8. Samphire or saline coastal flat	(Fox et al., 2001; Woinarski, Brennan, et al., 2003)
10	Sand dunes	*Kurlimipiti* *Pungamparna*	MT2.1 Coastal shrublands and grasslands	64. Other grasslands 27. Naturally bare - sand, rock, claypan, mudflat	7. Beaches, chenier ridges, grasslands	(Fensham, 1993; Brocklehurst & Edmeades, 1998; EcOz Environmental Services, 2012)
11	Sandy shorelines	*Tingata* (beach) *Wurrungalama*, *Yartila* (bare area) *Kuluwunila* (dry beach)	MT1.3 Sandy shore	27. Naturally bare - sand, rock, claypan, mudflat	-	(Chatto, 2001, 2003; Whiting et al., 2007)
12	Rocky shorelines	*Tingata* (outcrops in sandy beaches)	MT1.1 Rocky shore	27. Naturally bare - sand, rock, claypan, mudflat	-	-
Anthropogenic ecosystems						
13	Urban and modified	-	T7.4 Urban industrial	25. Cleared, non-native vegetation, building	-	-
			T7.5 Semi-natural pastures and old fields	29. Regrowth, modified native vegetation		
14	Plantation	-	T7.3 Plantation	25. Cleared, non-native vegetation, building	9. Plantations	-

[a] Global Ecosystem Typology
[b] National Vegetation Information System

Table 3. The confusion matrix for the classification of 11 of the ecosystem types on the Tiwi Islands, northern Australia.

	Training points												
Predicted type	Coastal salt marsh	Dry rainforest	Eucalypt savanna	Grassland and sedgeland	Mangrove	*Melaleuca* savanna	Treeless plains	Sand dunes	Sandy shoreline	Ocean	Wet rainforest	Total	UA	CE
Coastal salt marsh	269	0	0	6	1	0	0	0	11	2	0	289	0.93	0.07
Dry rainforest	0	816	0	0	4	0	0	0	0	0	19	839	0.97	0.03
Eucalypt savanna	0	6	743	19	5	6	7	9	0	0	7	802	0.93	0.07
Grassland and sedgeland	5	0	6	476	25	0	2	4	0	0	5	523	0.91	0.09
Mangrove	0	20	1	43	579	0	0	0	0	0	6	649	0.89	0.11
Melaleuca savanna	0	2	59	76	4	78	47	35	0	0	0	301	0.26	0.74
Treeless plains	0	0	13	17	0	8	138	34	0	0	0	210	0.66	0.34
Sand dunes	1	0	0	1	0	0	2	372	29	0	0	405	0.92	0.08
Sandy shoreline	6	0	0	0	0	0	0	15	334	0	0	355	0.94	0.06
Ocean	0	0	0	0	0	0	0	0	0	368	0	368	1.00	0.00
Wet rainforest	0	176	19	2	6	0	0	0	0	0	354	557	0.64	0.36
Total	281	1020	841	640	624	92	196	469	374	370	391	5,298		
PA	0.96	0.80	0.88	0.74	0.93	0.85	0.7	0.79	0.89	0.99	0.91			
OE	0.04	0.20	0.12	0.26	0.07	0.15	0.3	0.21	0.11	0.01	0.09			

PA: Producer's accuracy
UA: User's accuracy
OE: Omission error
CE: Commission error

Figures

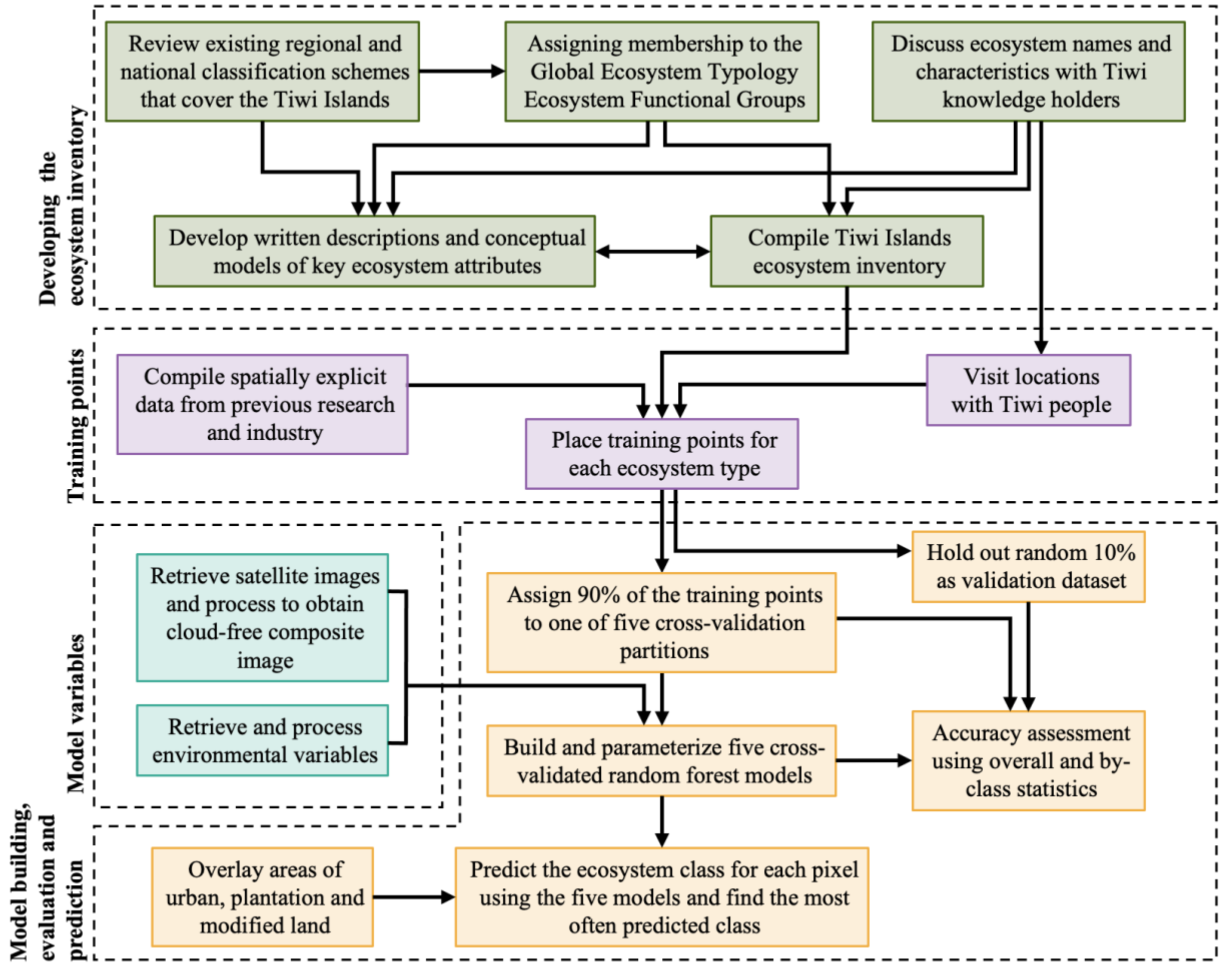


Figure 1. Overview of the methods to classify, describe, and map ecosystems using the Global Ecosystem Typology for the Tiwi Islands, Australia.

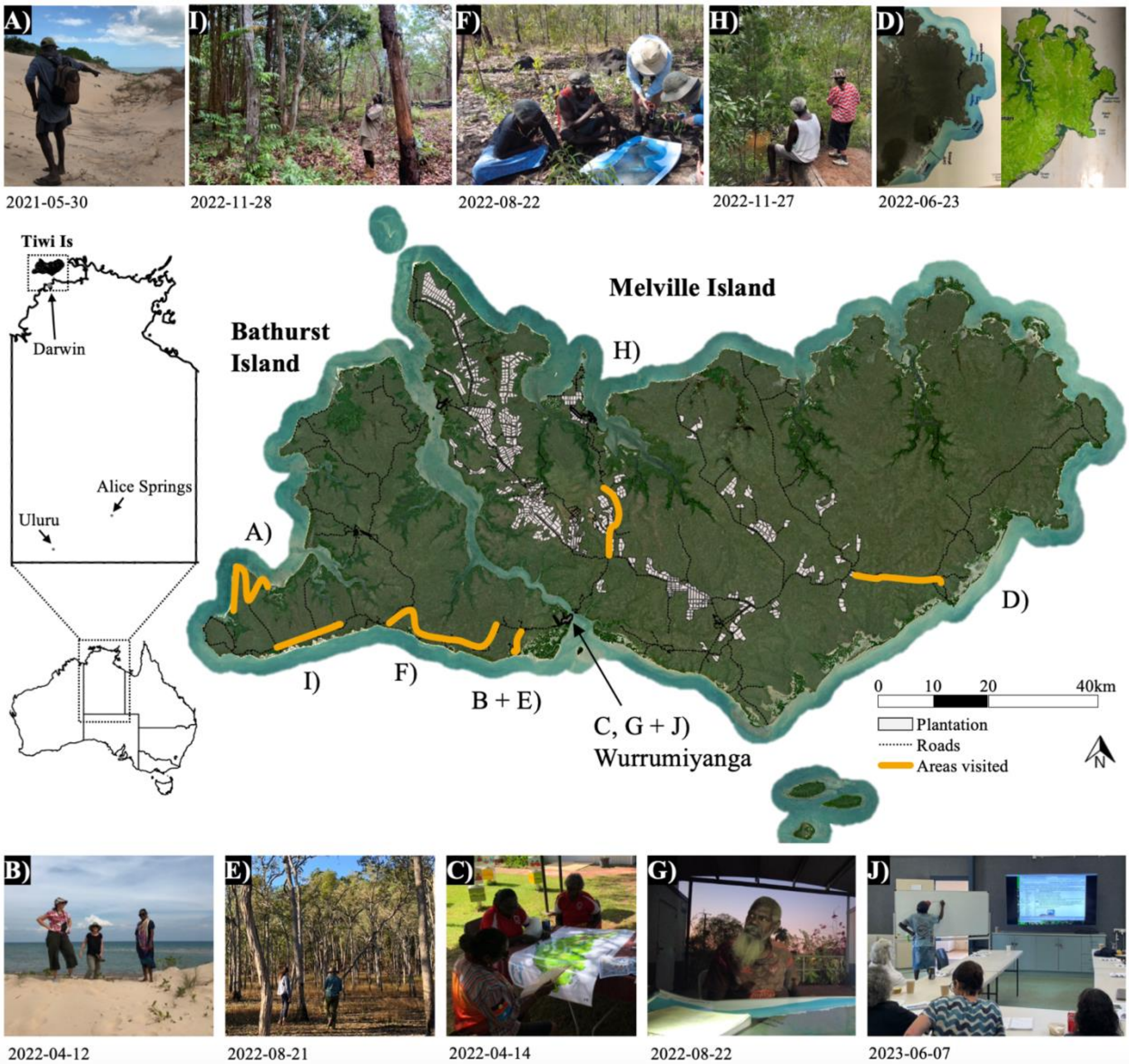


Figure 2. Examples of the consultation locations undertaken and photographs with the Tiwi knowledge authorities regarding types, names, and characteristics of ecosystems in Tiwi language.

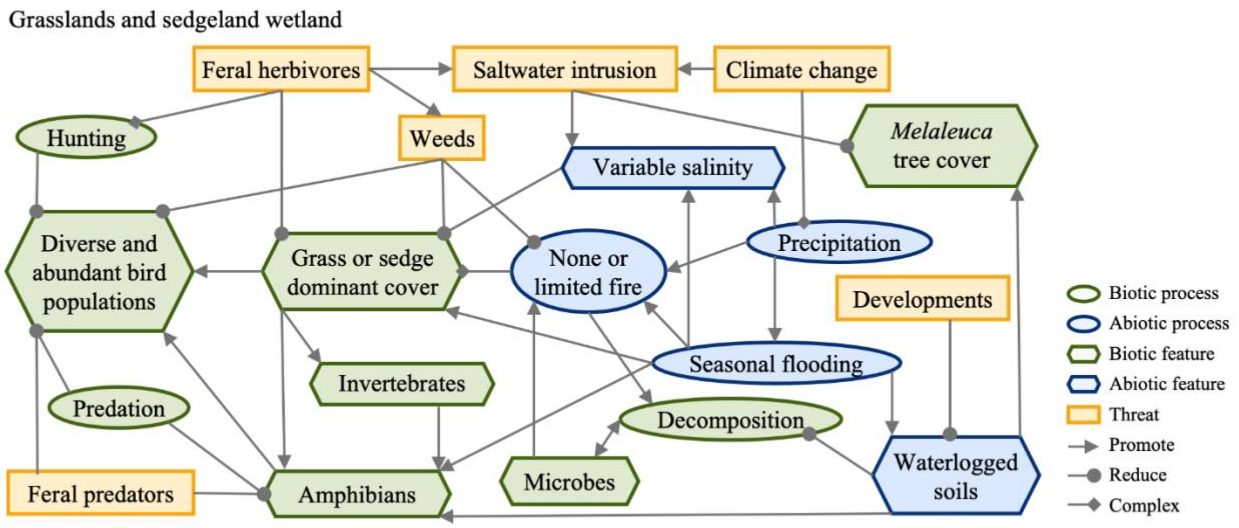


Figure 3. Exemplar cause-and-effect conceptual model of grassland and sedgeland wetlands (*turringiya*) on the Tiwi Islands, northern Australia, developed following Red List of Ecosystem guidelines (Keith, Ferrer-Paris, et al., 2024), which links ecosystem processes, attributes, and threats; similar models for each ecosystem type listed in Table 1 can be found in Appendix 7.

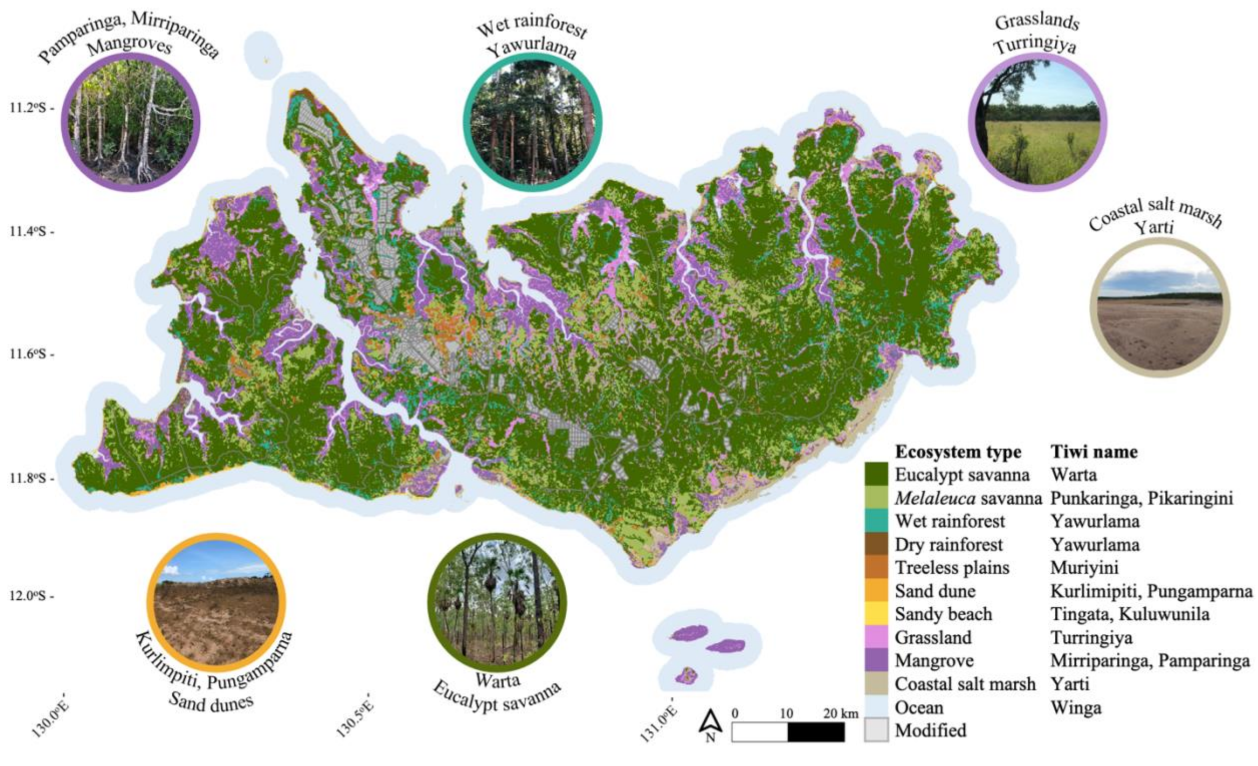


Figure 4. The distribution of the ecosystem types on the Tiwi Islands, Australia, with exemplar photos of select ecosystems.

Appendices

Appendix S1 - Developing the Tiwi Islands ecosystem inventory

Table 4. The dates, location and Tiwi People consulted regarding the names in Tiwi language and characteristics of ecosystems across the Tiwi Islands, Australia.

	Date	Names of people	Location
A)	30^{th} of May, 2021	Colin Kerinaiua	On-ground visit to south-western Bathurst Islands
B)	12^{th} of April, 2022	Mavis Kerinaiua	On-ground visit to Tarntipi in south-eastern Bathurst Island
C)	14^{th} of April, 2022	Fiona Kerinaiua and Ancilla Kurrupuwu, facilitated by Mavis Kerinaiua	Discussion in Wurrumiyanga
D)	23-24^{th} of June, 2022	Denis Dunn	On-ground visit to south-eastern Melville Island
E)	21^{st} of August, 2022	Marie Munkara and Kinjia Munkara-Murray	On-ground visit to south-eastern Bathurst Island
F)	22^{nd} of August, 2022	John Louis Munkara, Gemma Munkara and Kinjia Munkara-Murray	On-ground visit to southern Bathurst Island
G)	22^{nd} of August, 2022	Mario Munkara	Discussion in Wurrumiyanga
H)	27^{th} of September, 2022	Bernard Tipiloura	On-ground visit to central-west Melville Island
I)	28^{th} of September, 2022	Bernard Tipiloura, Colin Kerinaiua, and Simon Munkara	On-ground visit to south-west Bathurst Island
J)	7^{th} of June, 2023	Andrina Tipuamantamirri, Marie Carmel, Lorna Kantilla, Leetisha Tipuamantamirri, Ancilla Kurrupuwu, Jane Puautjimi, Marie Alimankinni, Alice Munkara, Karen Tipiloura, Yvette Tipuamantamirri, and Marie Tipiloura. Facilitated by Mavis Kerinaiua and undertaken as part of the Knowledge Database project.	Workshop in Wurrumiyanga

Table 5. Example questions use to guide conversations about ecosystems on the Tiwi Islands, Australia.

Example questions	Outcome
What sort of plants and animals do you find or use in places like this?	Ecosystem composition
Do places like this ever burn? Is the ground ever wet and doesn't drain?	Ecosystem processes
How are places like this different during wet season?	Seasonality
Is there are name for places which have these sorts of plants and animals living together? In the Tiwi Plants and Animals book, there is this word 'X'. Is that word the name for places like this?	Name of ecosystems
Where are other places that look like this?	Location of example areas
Are there many other places that look like this?	Extent
Have you seen any changes here or in areas like this? Does this look different to how you remember it in the past?	Change and degradation
What is damaging places like this?	Threats
Are there parts of Country which do not look like any of the ecosystems we have talked about? Are we missing any places?	Comprehensiveness

Appendix S2 - Training points

Aerial photos provided the most benefit for training point placement and essential information for off-road regions given much of the Tiwi Islands is inaccessible by car. Two sets of helicopter photographs were obtained. The first from CSIRO which were captured to undertake vegetation mapping for fire planning and savanna fire management. The second from a wildlife survey on Melville Island in 2023. Photographs from the wildlife and the fire planning on Melville Island were coded to identify the ecosystems present in the image and a degree of certainty. All uncertain classifications were removed. The ecosystems recorded were mangrove, grasslands, forested savanna, woodland savannas, rainforests, treeless plains, sand dunes, bare sand, water, and forestry plantations.

To supplement the previous research which identified multiple ecosystems, we also investigated and used research and products relating to individual ecosystem. Rainforest patches were the best documented ecosystem with multiple resources available to provide training points. The most informative resources were the Tiwi Plantation Corporation coup maps and data. The Tiwi Plantation Corporation maps have high-quality information on the spatial distribution of rainforest patches adjacent to the coups for land clearing regulations. Tiwi Plantation Corporation have also undertaken surveys for weeds in the adjacent rainforest patches. GPS tracks from the 2018-2020 surveys and the coup map PDFs were overlayed with satellite imagery to identify rainforest patch locations. Given the plantation coups are spatially aggregated towards western Melville, other resources were explored to identify rainforest patches away from the forestry operations. The NT government also provided useful resources for rainforest. Threatened and endemic plants on the Tiwi Islands are overrepresented in rainforests compared to other ecosystems (Liddle and Elliott, 2008). Locations of rainforest patches were also obtained from targeted rainforests surveys. The locations of the full floristic inventories were extracted from the NT Flora database. Ant survey locations were provided by Prof Alan Anderson (Andersen *et al.*, 2012) and Kinjia Munkara-Murray (unpublished data from 2022). Rainforest mammal surveys were undertaken in 1992 (Menkhorst and Woinarski, 1992). Distinctive species for the rainforest types were observed by Russell-Smith (1991) and reported by Brocklehurst and Edmeades (1998). We investigated using Atlas of Living Australia occurrence points for these distinctive species; however, the occurrence points did not overlap with rainforest patches when overlayed with a satellite image, potentially due to spatial uncertainties in the GPS points.

Apart from rainforest ecosystems, all other ecosystems tended to have one previous resource to support the creation of training points. For eucalypt forested savannas, mammal surveys undertaken by Dr Hugh Davies (Davies *et al.*, 2018) and Georgina Neave (Neave *et al.*, 2024) in the eucalypt savanna were included. For treeless plains, we used the historical extents of the vegetation communities by Wilson and Fensham (1994) and verified locations on-ground for spatial accuracy. Coarse maps of the sand dune extent in south west Bathurst Island were obtained from the Matilda's mining proposal (EcOz Environmental Services, 2012).

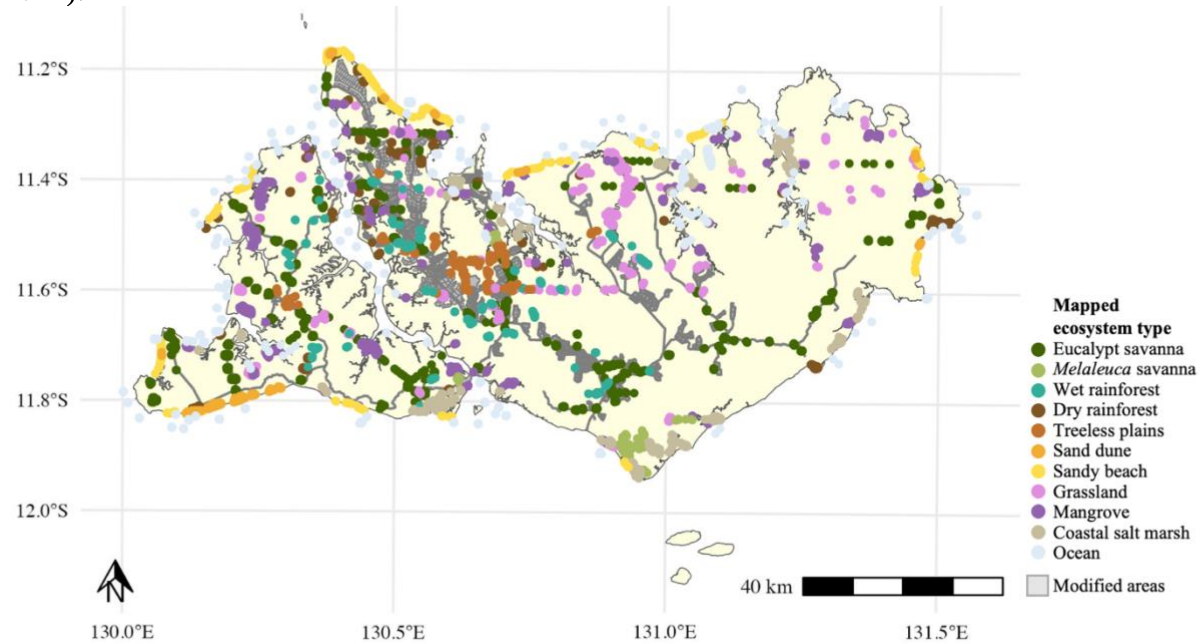
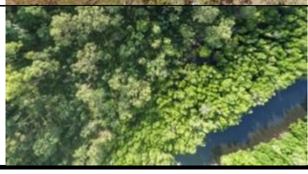
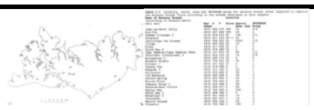
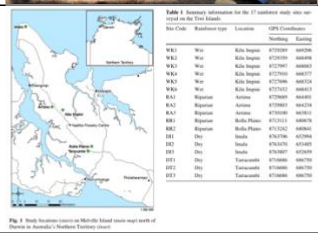
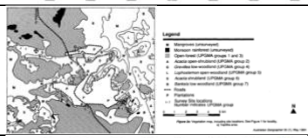


Figure 5. Location of the 5, 298 points used to train the classification model for each of the ecosystem types which were able to be mapped (colors).

Table 6. Details of the datasets used to develop training points.

Date	Names of people or organisations involved	Details and location	Example of the data
Aerial photographs			
2013	Commonwealth Scientific and Industrial Research Organisation (CSIRO)	Helicopter survey undertaken to classify vegetation into four classes based on the inclusion or exclusion form the savanna fire management program and supplied by the Tiwi Land Council.	
2022	Tiwi Land Council	Wildlife survey covering Melville Island in horizontal transects and supplied by the Tiwi Land Council.	
Research and consultancy reports			
November 2006	David Liddle and L.P. Elliot	Location of the rainforest patches which were surveyed to assess threatened plants and threatening processes (Liddle and Elliott, 2008).	
2015, 2021 and 2022	Dr Hugh Davies and Georgina Neave	Sampling of mammals in Eucalypt open forest savanna and Eucalypt and mixed species savanna systems (Davies *et al*., 2018; Neave *et al*., 2024).	
2012 and 2021	Professor Alan Andersen and Kinija Munkara-Murray	Sites of ant and invertebrate sampling in wet and dry rainforests for government and academic research (Andersen *et al*., 2012).	
Unknown	Tiwi Plantation Corporation	Maps of the plantation coups and surrounding rivers and rainforest patches prepared by Tiwi Plantation Corporation and supplied by the Tiwi Land Council.	
May 1994	Bruce Wilson and Roderick Fensham	PhD thesis and paper regarding the classification and mapping of the vegetation types within the 'treeless plains' ecosystem. (Wilson and Fensham, 1994)	
July 2012	EcOz Environmental Services	Sand mining proposal and assessments undertaken by EcOz consultant for Matilda Zircon (EcOz Environmental Services, 2012).	 Figure 3: Location of the four target dunes at Kilimiraka

Appendix S3 – Model variables: satellite imagery

We used Landsat-9 images from level 2, collection 2, tier 1 with a spatial resolution of 30 m were obtained from GEE https://developers.google.com/earth-engine/datasets/catalog/LANDSAT_LC09_C02_T1_L2 . Landsat-9 is provided open-access, courtesy of the United Stated Geological Survey (USGS). We applied a scaling factor to the images as per the Landsat guidelines with the code written by GEE and translated to R by Cesar Aybar https://github.com/csaybar. For the optical bands, the band was first multiplied by $2.75*e^{-5}$ then minus 0.2. For the thermal bands, the band was first multiplied by $3.41802*e^{-3}$ then add 149.

To obtain a cloud-free satellite image in the tropical and cloudy location, we tested multiple methods of filtering and processing the image bands. We tested compiling the images starting in January, February, and March, and ending in April and May (total of 6 time periods). We focused on images after December to allow for vegetation growth in the wet season and before June to limit the effect of fires. For each of these periods, we tested using a single year (2023), two years (2022-2023) or three years (2021-2023). We tested filtering each of these time periods (n = 18) by 4 different cloud cover percentage upper limits: 20%, 30%, 40% and 50% (n = 72). The cloud cover is precalculated for the whole image and does not account for the cloud being over the study region or the ocean. We masked the image using the quality assessment (QA) bands for the cloud and cloud shadow (bits 3 and 5). Each of the 72 stacks of images were composited into a single image using the median, resulting in 72 potential image options. We visually inspected each composite image for residual cloud effects.

The final image was a single-year composite for 2023 of late wet season and early dry season images (January to May) with less than 30% cloud cover and the remaining clouds removed with a QA-pixel mask. Increasing the number of months and the number of years always increased the number of images available and improved the final map. However, this is traded-off with obtaining the most up-to-date and accurate image. A maximum cloud cover of 30% seemed to balance well removing the high cloud cover images while also retaining enough images in the stack to create a composite. A smaller filter for cloud cover (i.e. 20%) resulted in extensive residual cloud and cloud shadows. A high cloud threshold filter (i.e. 40-50%) resulted in too few images in the stack and non-complete coverage of the study region.

Appendix S4 – Model variables: environmental layers

We tested the covariate correlation using the Pearson's correlation coefficient with a |0.7| cut-off. The red, green and blue satellite image bands were highly, positively correlated ($r > 0.96$). Red performed as the best predictor on its own and had the lowest correlation with NDVI. Slope and Topographic Position Index were correlated ($r > 0.99$) but added no explanatory power to the model and hence were removed from the candidate variables. All three vegetation height variables were highly positively correlated ($r > 0.77$). The height at which 95% of the biomass is intercepted performed the best as an individual predictor.

Table 7. Details of the environmental layers used as model covariates.

Layer	Name or description	Rational	Source
Elev	Elevation	The elevation is a proxy for range of environmental relationships including access to groundwater, influence of floods, exposure to wind on hilltops, and exposure to wave disturbances on coastal ecosystem. The topographic	The Smoothed Digital Elevation model (DEM-S) at a 5 m resolution from the Shuttle Radar Topography Mission (SRTM) by from Geoscience Australia in 2000 https://developers.google.com/earth-engine/datasets/catalog/AU_GA_DEM_1SEC_v10_DEM-S

Slp	Slope in degrees	measures also relate to soil moisture and run off which strongly drive ecosystem functioning.	Created using the ‘terrain’ function from the ‘terra’ package in R on the elevation model. Slope was computed with the four neighbouring cells and measured in degrees.
TPI	Topographic position index		
Height_95	The height where 50, 75 and 95% of the vegetation biomass has been intercepted.	The height of the vegetation biomass indicates the vegetation structure.	Terrestrial Ecosystem Research Network https://portal.tern.org.au/metadata/TERN/de1c2fef-b129-485e-9042-8b22ee616e66
Height_75			
Height_50			
Red	The red (B4), green (B3), blue (B2) and near infrared (B5) bands from the Landsat-9 composite image.	Spectral characteristics represent physical and chemical attributes of the ecosystem.	The cloud-free composite Landsat-9 image was the median of the images between January to May of 2023 with less than 30% cloud cover and the remaining cloud removed with a QA-pixel mask.
Green			
Blue			
NIR			
NDVI	The normalised difference vegetation index.	Greenness of the canopy which is correlated to primary productivity.	Calculated from the Landsat-9 image using the red (B4) and near infrared (B5) bands where: $NDVI = \frac{NIR - Red}{NIR + Red}$

Appendix S5 - Model building, evaluation and prediction

We optimised the random forest classification model parameters, testing 1) the number of trees from 10 to 200 in intervals of 10, 2) splitting nodes using 1 to 5 randomly selected variables and 3) a tree depth of 1 and the even numbers from 2 to 10 inclusive. We also tested equal sample sizes for all categories by taking a random subset the points to the number in the smallest category (i.e. down-sampling), however pilot models showed the results were very similar to weighting the classes in the model.

Given the confusion matrix below, the accuracy metrics were calculated as:

		True	
		1	0
Predicted	1	A	B
	0	C	D

1. User’s accuracy (a.k.a Positive predicted value, precision) = A / (A + B)
2. Producer’s accuracy (a.k.a Sensitivity, recall, true positive rate) = A / (A + C)
3. Commission error = 1 - User’s accuracy
4. Producer’s error = 1 - Producer’s accuracy
5. Accuracy = (A + D) / (A + B + C + D)
6. Kappa statistic = (2 * (A*D – B*C)) / ((A+C) * (C+D) + (A+B) * (B+D))

R packages

Satellite imagery:

‘rgee’ (version 1.1.6.9999) (Aybar *et al.*, 2020)

‘rgeeExtra’ (version 0.0.1) (Aybar *et al.*, 2020)

Data cleaning and manipulation:

‘dplyr’ (version 1.1.2) (Wickham *et al.*, 2023)

Spatial data cleaning:

‘terra’ package (version 1.7-29) (Hijmans, 2023)

‘enmSdmX’ (version 1.1.2) (Smith *et al.*, 2023)

‘sf’ (version 1.0-14) (Pebesma, 2018; Pebesma and Bivand, 2023)

Model:

‘ranger’ (version 0.15.1) (Wright and Ziegler, 2017)

Visualisations:

‘tidyterra’ (version 0.4.0) (Hernangomez, 2024)

‘ggplot2’ (version 3.4.3) (Wickham, 2016)

Appendix S6 – Additional model results

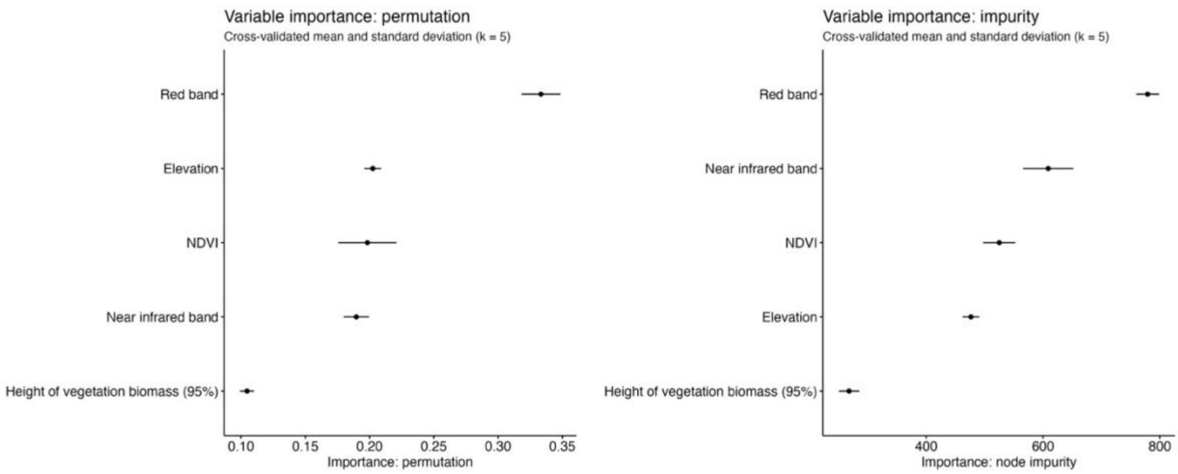


Figure 6. Importance of the model covariates as measured by the permutation (left) and node impurity (right). The dot represents the mean importance from the five cross-validation folds and the bar represents the standard deviation.

A) Accuracy B) Kappa

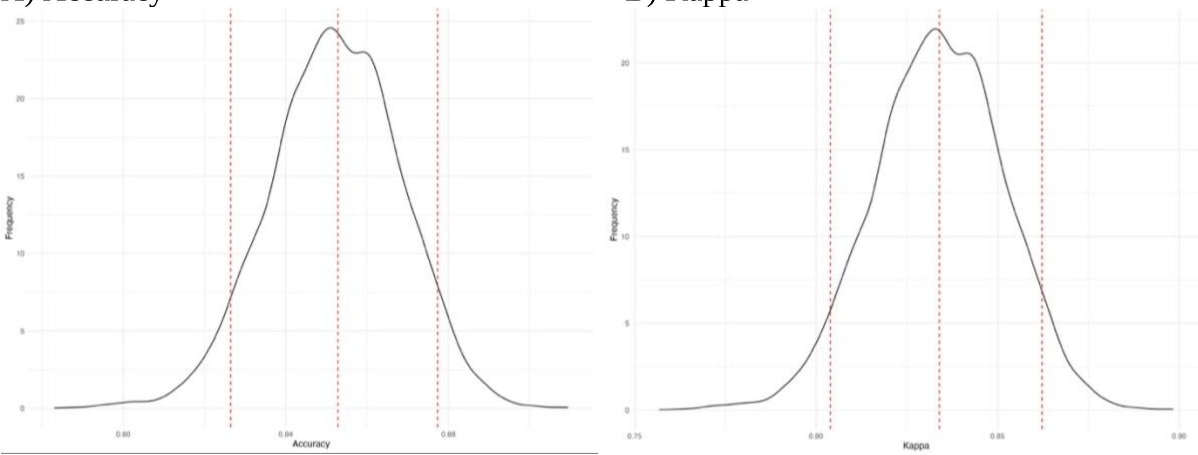


Figure 7. Overall measures of accuracy (left) and kappa (right) from 10, 000 model runs on a randomly selected 90% of the training data. The dashed red lines represent the 5, 50 and 95% quantiles. The median accuracy was 85.28% (82.64 – 87.74) and kappa was 83.40% (80.39 – 86.23).

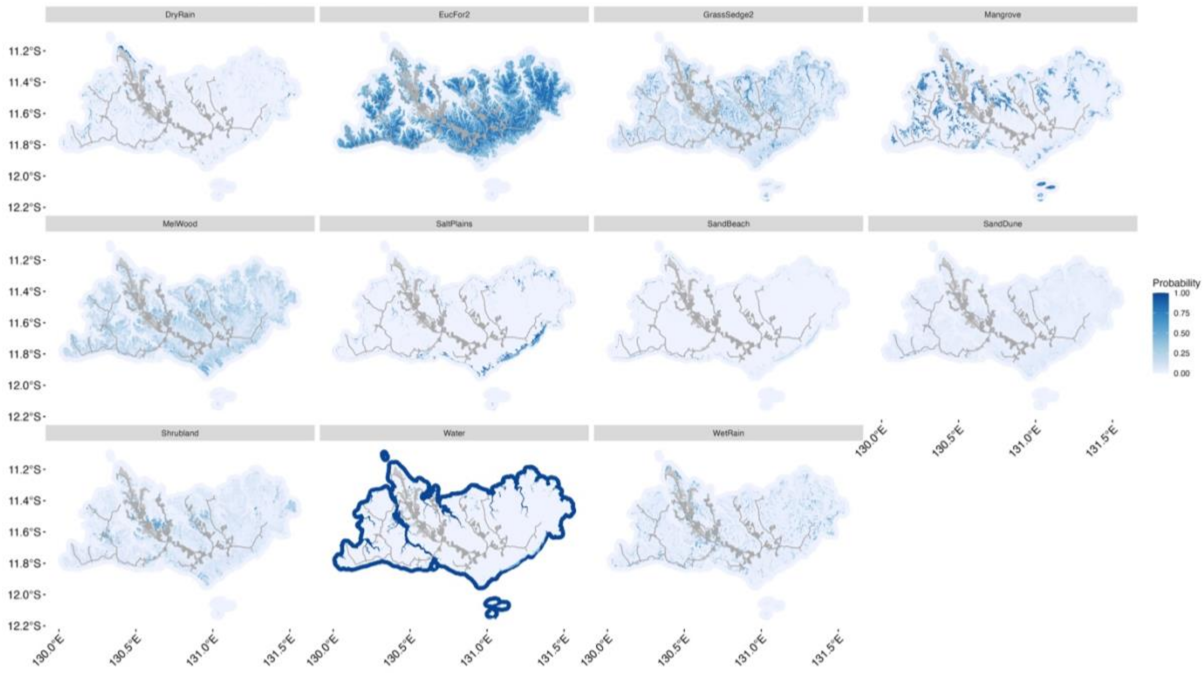


Figure 8. The predicted probability of each ecosystem from the random forest classification model for the Tiwi Islands, Australia.

Appendix S7 – Ecosystem descriptions, photographs, and conceptual models

A public repository and DOI will be made available upon acceptance of the paper.

Eucalypt open forest savanna. Warta.

Ecosystem function

Eucalypt open forest savanna (warta in Tiwi language) is a tropical savanna ecosystem classified by discontinuous tree cover over a grassy understory and driven by the presence of fire (Keith *et al.*, 2020). Fire is the key ecological process in pyric savannas such as on the Tiwi Islands (Williams *et al.*, 2017; Keith *et al.*, 2020). Fires in the Australian tropics are frequent and low-intensity (Murphy *et al.*, 2013). The Tiwi Island savanna produces a taller and denser canopy than other regions of the Northern Territory, driven by high rainfall (Woinarski, Brennan, Cowie, *et al.*, 2003; Williams *et al.*, 2017). Tree height and canopy cover, as well as the floristics and density of understorey plants, vary substantially although the relationship with water availability, pyric and edaphic factors is unclear (Fensham and Kirkpatrick, 1992; Brocklehurst and Edmeades, 1998). Recent fire is suggested to influence the structural variation is suggested, rather than ecological or edaphic factors (Woinarski, Brennan, Cowie, *et al.*, 2003). The soils are well-drained, generally deep red earths to sandy loams, with laterite in the soil profile impeding tree growth (Wilson and Bowman, 1994; Woinarski *et al.*, 2000). The ecosystem experiences seasonal drought from April to October and no waterlogging or free-standing water during the wet season (November to March) (Fensham and Kirkpatrick, 1992).

Geographic extent

On the Tiwi Islands, eucalypt open forest savanna dominates the landscape with 76% and 73% coverage on Melville and Bathurst Islands, respectively (Wilson *et al.*, 1990; Woinarski *et al.*, 2000; Woinarski and Baker, 2002; Woinarski, Brennan, Cowie, *et al.*, 2003). Due to the high rainfall on the Tiwi Islands, the eucalypt savanna produces a denser canopy (although still open) than in other regions of the Northern Territory (Williams *et al.*, 2017). Vast expanses of eucalypt savanna span the Northern Territory (Wilson *et al.*, 1990), as well as northern Australia (Fox *et al.*, 2001; Williams *et al.*, 2017; DCCEEW, 2020) and globally (Keith *et al.*, 2022).

Flora

Eucalypt open forest savanna exists as consistent assemblage of canopy species which vary in dominance and cover. These canopy species are *Eucalyptus miniata* (Darwin woollybutt, timirraringa), *E. tetrodonta* (Darwin stringybark, jukwartirringa), and the unique codominance of *Corymbia nesophila* (Melville Island bloodwood, wurringilaka) (Brocklehurst and Edmeades, 1998; Woinarski, Brennan, Cowie, *et al.*, 2003). The savanna is tall, generally with a canopy between 15 and 25 m high and reaching 15 to 30 % canopy cover (Woinarski *et al.*, 2000). *Erythrophleum chlorostachys* (Ironwood, karunkuni) provides crucial wood for carving and varies in prevalence (Fensham and Kirkpatrick, 1992; TLC *et al.*, 2001; Taylor, 2002). Intermittent patches of the fire-sensitive *Callitris intratropica* appear mosaiced through topographically protected areas. The variety in structural forms and floristic composition highlight that this ecosystem type represents multiple vegetation types. The slight floristic variation in the eucalypt open forest savanna renders it difficult to define within the land units system as the changes in the dominant tree species did not seem to match with the composition in the understory (Woinarski, Brennan, Cowie, *et al.*, 2003). Eucalypt open forest savanna is distinct from the more variable eucalypt and mixed-species savanna on the Tiwi Islands and from mainland formations by the taller and denser canopy, driven by high rainfall, and a consistent canopy species composition. Diverse mid-storey vegetation provides food resources for people and animals (Woinarski, 1990); the cycad *Cycas armstrongii* (vulnerable$_{NT}$, minta), and shrub species *Buchanania obovata* (Green plum, yankumwani), *Terminalia ferdinandiana* (Billy goat plum, pirlamunga), *Planchonia careya* (Cocky apple, kanuli), and the palm *Livistona humilis* (Sand palm, miparri) (Woinarski and Baker, 2002). Eucalypt savanna hosts medicinal plants, including *Persoonia falcata* (jimijinga), *Ficus* spp. (tokapunga), *Planchonia careya* (kanuli), *Eucalyptus miniata* (timirraringa) and *Pandanus spiralis* (miyaringa)(TLC *et al.*, 2001; Thompson *et al.*, 2019). The understory of annual and perennial tussock grasses includes *Eriachne* sp. and *Sorghum* sp. (marakati). Compositionally, Tiwi open forest savannas appear similar throughout the Tiwi-Coburg bioregion (Woinarski and Baker, 2002). On the Tiwi Island, the Eucalypt open forest savanna ecosystems supports the threatened and endemic arum lilies *Typhonium jonesii* (endangered$_{NT,AUS}$, jilarringa) and *Typhonium mirabile* (endangered$_{NT,AUS}$) and one species listed as Data Deficient by the Northern Territory Government, *Pecteilis elongata* (Woinarski *et al.*, 2000; Woinarski, Brennan, Cowie, *et al.*, 2003; Liddle and Elliott, 2008).

Fauna

The eucalypt open forest savanna providex essential habitat to a range of animals by providing food resources from shrubs, highly abundant tree hollows for nesting, and cover from predators (Woinarski and Westaway, 2008; Woolley *et al.*, 2018; Penton, 2021). Threatened mammals in the eucalypt savanna include the endangered the brush-tailed rabbit-rat (vulnerable$_{AUS}$, endangered$_{NT}$, *Conilurus penicillatus*, wurruwataka) and the northern brush-tailed phascogale (vulnerable$_{AUS}$, endangered$_{NT}$, *Phascogale pirata*), the vulnerable butler's dunnart (vulnerable$_{AUS, NT}$, *Sminthopsis butleri*, wurruwataka), northern brushtail possum (vulnerable$_{AUS}$, *Trichusurus vulpecula arnhemensis*, wuninga), and black-footed tree-rat (vulnerable$_{AUS, NT}$, *Mesembriomys gouldii melvillensis*) (Woinarski, Brennan, Hempel, *et* *al.*, 2003; Woinarski, 2004a; Firth *et al.*, 2006; Davies *et al.*, 2018; Department of Environment, Parks and Water Security, 2021b, 2021c, 2021l; Davies, Rangers, *et al.*, 2021; von Takach *et al.*, 2023). The rabbit-rat and tree-rat appear restricted to this eucalypt forest ecosystem (Woinarski, 2000). Other common small- and medium-sized mammals within the eucalypt open forest savanna include the agile wallaby (*Notamacropus agilis,* anjorra), savanna glider (*Petaurus ariel,* rajinga*)*, and northern brown bandicoot *(Isoodon macrourus,* kipopi/marinyi) (Woinarski, Brennan, Hempel, *et al.*, 2003). The possum and bandicoots are hunted, albeit to a lesser degree than historically (TLC *et al.*, 2001).

Compared to other ecosystems, the eucalypt open forest savanna contains lower bird species richness and abundance (Fensham and Woinarski, 1992). Significant populations of three threatened birds are common on the Tiwi Islands: 1) a sub-species of the partridge pigeon (vulnerable$_{NT,AUS,}$ *Geophaps smithii smithii*, mapulinka) (Woinarski, 2004b; Davies *et al.*, 2019; Department of Environment, Parks and Water Security, 2021o), unusually high densities of the large Red goshawk (vulnerable$_{AUS, NT}$, *Erythrotriorchis radiatus*) (Department of Environment and Natural Resources, 2006a), and the endemic subspecies, the Tiwi masked owl (endangered$_{AUS, NT}$, *Tyto novaehollandiae melvillensis*)(Department of Environment, Parks and Water Security, 2021j). Red-winged parrots (*Aprosmictus erythropterus,* artirringarika) and the Australian owlet-nightjar (*Aegotheles cristatus*) utilise the extensive hollows (Penton *et al.,* 2021).

The eucalypt open forest savanna supports many other animals. Ants are diverse and abundant, with nearly 100 species, including endemic species (Andersen, Woinarski and Hoffmann, 2004). Common reptiles are the frill-neck lizard (*Chlamydosaurus kingii*, kurupurrani/kuntamani), carpet python (*Morelia spilota*, yilinga), sand goanna (*Varanus gouldii*, kawarri/muwani), the gecko *Heteronotia binoei*, and the skink *Glaphyromorphus darwinensis.* Pythons and goannas are hunted for food (TLC *et al.*, 2001). In tree hollows, the spotted tree monitor (*Varanus scalaris*), and the black-headed monitor (*V. tristis*) can be found (Penton *et al.*, 2021). The Dodd's Azure butterfly (endangered$_{NT}$, *Ogyris iphis doddi*) (Department of Environment, Parks and Water Security, 2021d) is also present and threatened, although little research is available.

Potential threats

Tropical savannas are one of the most sensitive ecosystems in Australia, where minor degradation may cause a large loss in the ecosystem functioning (Laurance *et al.*, 2011). As fire is a prominent process in pyric savannas, changes to the natural fire regimes (i.e. inappropriate fire regimes), such as by high frequency and severity, could threaten the eucalypt open forest savanna through changes to the structural and composition of the vegetation, the persistence of animals and the ecological processes that maintain the ecosystem integrity (Murphy *et al.*, 2013, 2023; Williams *et al.*, 2017). Many common and threatened species are severely negatively impacted by severe fires by the loss of food resources and hollows (Woinarski, 2004b; Firth *et al.*, 2006; Davies, Visintin, *et al.*, 2021). Altered fire regimes also impact carbon storage and nitrogen cycling (Laurance *et al.*, 2011). Fire regimes may continue to change with variable weather due to climate change and the desire to protect developments. Additional alterations to the ecological function of the eucalypt open forest savanna may result from the increase atmospheric carbon, increasing temperature, and changes to precipitation patterns due to climate change (Williams *et al.*, 2017). Weed invasion is the biggest threat to tropical savannas across Australia (Laurance *et al.*, 2011), particularly through interactions with fire. Grassy weeds are detrimental to tropical savanna ecosystems by outcompeting native grasses and by increasing fire severity in a positive feedback loop, namely gamba grass (*Andropogon gayanus*), *Sida acuta*, and mission grass (*Cenchrus polystachios*) (Woinarski, Hadden, Hicks, *et al.*, 2003; EcOz Environmental Consultants, 2021). Invasive animals also threaten the eucalypt open forest ecosystem in multiple ways. On the Tiwi Islands, feral cats predate mammals, birds and reptiles, reducing the abundance of already threatened species (Woinarski, 2004a; Davies et al., 2017; Neave et al., 2024). The effect of cats on the Tiwi Islands seems to interact with other threatening and disturbance processes, largely fire (Davies, Maier and Murphy, 2020; Neave et al., 2024). Invasive ungulates, particularly buffalo (*Bubalus bubalis*) and pigs (*Sus scrofa*) may overgraze ground-level plants, trample undergrowth, spread weeds and reduce water quality through wallowing (Woinarski and Baker, 2002; EcOz Environmental Consultants, 2021). Historically, large tracts of eucalypt open forest savanna was cleared for plantations and linear corridors for roads (Department of Lands, Planning and Environment, 2000; Department of Infrastructure, Planning and Logistics, 2022). While eucalypt open forest savanna covers extensive areas of the Tiwi Islands, further clearing could threaten dispersal processes of species with ecosystem-wide impacts due to fragmentation (Laurance *et al.*, 2011).

Table 8. Cross-reference of the eucalypt open forest savanna ecosystem to eight classification schemes spanning the global, national, state, and regional scales.

Tiwi Island ecosystem types	Global Ecosystem Typology ecosystem functional group (level 3)[1]	International Vegetation Classification formations (level 3)[2]	NVIS major vegetation group[3]	NVIS major vegetation sub-group[3]	Northern Territory vegetation map[4]	Northern Territory macrogroups[5]	Generalised vegetation types of the Tiwi Islands[6]	Tiwi Island vegetation map[7]
Eucalypt open forest savanna	T4.2 Pyric tussock savanna	T3.a. Tropical savanna	3. Eucalypt open forests	5. Eucalypt open forest with grassy understory 7. Tropical Eucalyptus forest and woodlands with a tall annual grassy understorey 9. Eucalyptus woodlands with a tussock grass understorey	3. *Eucalyptus miniata* (Darwin woolly butt), *E. tetrodonta* (stringybark) & *Corymbia nesophila* (Melville Island bloodwood) open-forest with *Sorghum grassland* understorey	MG4. Australian Darwin Stringybark *Eucalyptus tetrodonta* Scleromorphic Woodland (M530; Muldavin *et al.* 2021)	1a: *Eucalyptus miniata* (Darwin woolly butt), *E. tetrodonta* (stringybark) & *Corymbia nesophila* (Melville Island bloodwood) open-forest with *Chrysopogon fallax* (golden beard grass) grassland understorey 1b: *Eucalyptus miniata* & *E. tetrodonta* open forest/woodland with tussock grassland understorey 1e: *Eucalyptus miniata* with *Eriachne triseta* tussock grassland understorey 1i: *Callitris intratropica* open-forest/woodlands with mixed *eucalyptus* species	Eucalypt forest dense Eucalypt forest mid-open Eucalypt forest open

[1] Keith, D. A., Ferrer-Paris, J. R., Nicholson, E., Bishop, M. J., Polidoro, B. A., Ramirez-Llodra, E., Tozer, M. G., Nel, J. L., Mac Nally, R., Gregr, E. J., Watermeyer, K. E., Essl, F., Faber-Langendoen, D., Franklin, J., Lehmann, C. E. R., Etter, A., Roux, D. J., Stark, J. S., Rowland, J. A., Brummitt, N.A., Fernandez-Arcaya, U.C., Suthers, I.M., Wiser, S.K., Donohue, I., Jackson, L.J., Pennington, R.T., Iliffe, T.M., Gerovasileiou, V., Giller, P., Robson, B.J., Pettorelli, N., Andrade, A., Lindgaard, A., Tahvanainen, T., Terauds, A., Chadwick, M.A., Murray, N.J., Moat, J., Pliscoff, P., Zager, I. and Kingsford, R. T. (2022). A function-based typology for Earth's ecosystems. *Nature*, *610*(7932), Article 7932. https://doi.org/10.1038/s41586-022-05318-4

[2] Faber-Langendoen, D., Keeler-Wolf, T., Meidinger, D., Tart, D., Hoagland, B., Josse, C., Navarro, G., Ponomarenko, S., Saucier, J.-P., Weakley, A., & Comer, P. (2014). EcoVeg: A new approach to vegetation description and classification. *Ecological Monographs*, *84*(4), 533–561. https://doi.org/10.1890/13-2334.1

[3] DCCEW. (2020). *National Vegetation Information System* (Version 6) [Computer software]. Australian Government. https://www.dcceew.gov.au/environment/land/native-vegetation/national-vegetation-information-system/data-products

[4] Wilson, B. A., Brocklehurst, P. S., Clark, M. J., & Dickonson, K. J. M. (1990). *Vegetation survey of the Northern Territory, Australia, 1990.* [Photos]. NT Map Shop.

[5] Hunter, J.T., Lewis, D., Addicott, E., Luxton, S., Cowie, I., Sparrow, B. and Leitch, E. (2022). A plot-based analysis of the vegetation of the Northern Territory, Australia: a first assessment within the International Vegetation Classification framework', *Vegetation Classification and Survey*, 3, pp. 161–174. Available at: https://doi.org/10.3897/VCS.83045.

[6] Brocklehurst, P., & Edmeades, B. (1998). Vegetation communities. In *The history and natural resources of the Tiwi Islands, Northern Territory*. Parks and Wildlife Commission of the Northern Territory.

[7] Woinarski, J. C. Z., Brennan, K., Cowie, I., Kerrigan, R., & Hempel, C. (2003). *Biodiversity conservation on the Tiwi Islands, Northern Territory: Part 1. Environments and plants*.

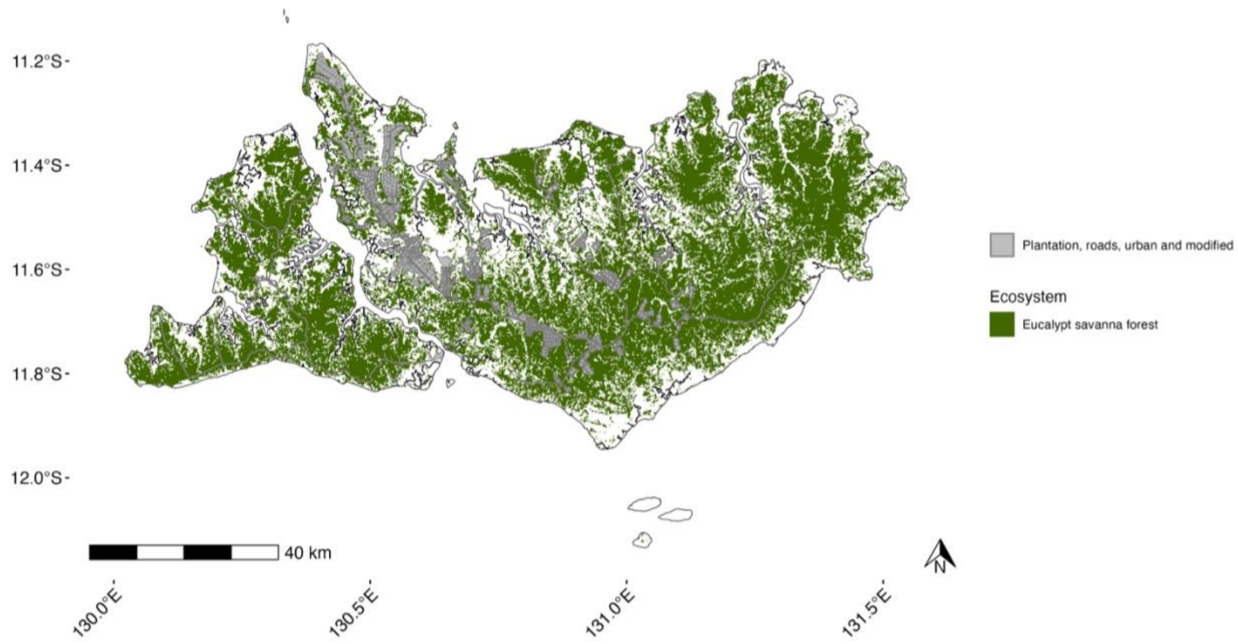


Figure 9. Map of the spatial distribution of the eucalypt savanna which represents the eucalypt open forest savanna and the eucalypt and mixed-species savanna on the Tiwi Islands, Australia.

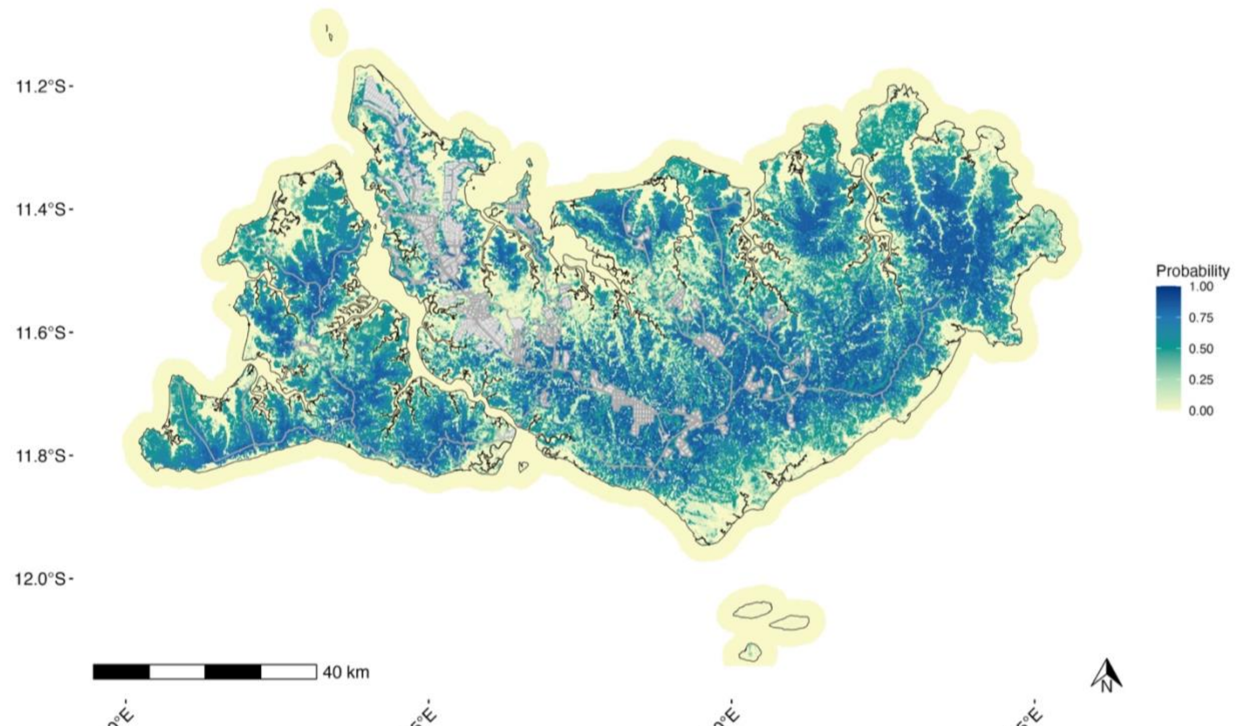


Figure 10. The prediction probability of the eucalypt savanna mapped class which represents the eucalypt open forest savanna and the eucalypt and mixed-species savanna on the Tiwi Islands, Australia from the random classification model.

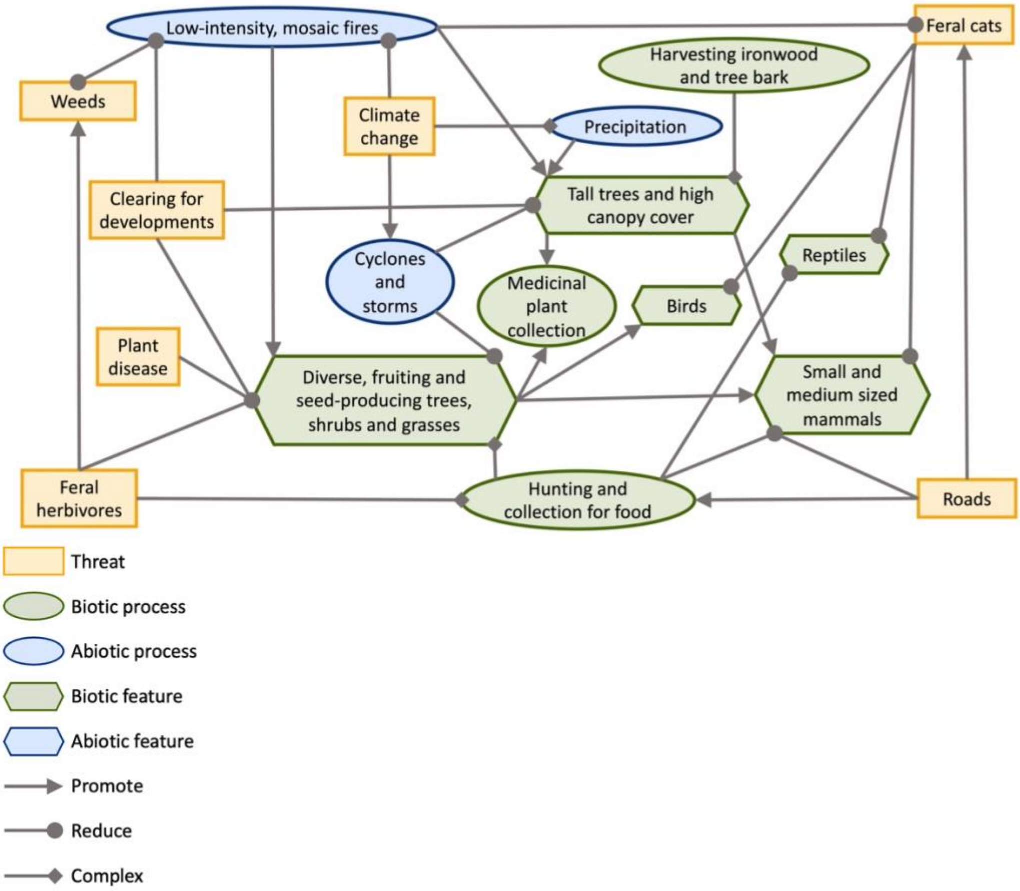


Figure 11. Cause-and-effect conceptual model based on the Red List of Ecosystem conceptual model structure for the Eucalypt open forest savanna ecosystem.

Figure 12. Images of the eucalypt open forest savanna ecosystem on the Tiwi Islands, Australia.

Eucalypt and mixed-species savanna. *Warta.*

Ecosystem function

The eucalypt and mixed-species savanna (warta in Tiwi language) is characterised by a variable species composition with a range of dominant canopy species from the *Eucalyptus* and *Corymbia* genera, and the resulting in structural variation. This variation in the vegetation community is driven by edaphic factors and soil moisture (Brocklehurst and Edmeades, 1998). This ecosystem is a tropical savanna with mixed-species tussock grassy groundcover and discontinuous tree cover (Keith *et al.*, 2020). The eucalypt and mixed-species savanna occurs in a variety of landforms, occupying areas with both poor drainage and dry substrates (Fensham and Kirkpatrick, 1992). Such landforms include lower rainfall areas, rises and crests, coastal plains, lower slopes and drainage flats, or in soils with higher gravel content, shallower depth and lower nutrients (Wilson *et al.*, 1990; Brocklehurst and Edmeades, 1998; Woinarski *et al.*, 2000; Woinarski, 2004c). The eucalypt and mixed-species savanna is the only ecosystem recorded with high surface gravel and rock outcrops (Brocklehurst and Edmeades, 1998). This variation in the environmental conditions in which the ecosystem occurs indicates this ecosystem could be further divided into finer ecosystem types by soil moisture content and is grouped here due to the small spatial extent and the availability of information. Fire is a key ecological process in pyric savannas such as the Tiwi Islands eucalypt and mixed-species savanna (Williams *et al.*, 2017; Keith *et al.*, 2020). Typically, fires would be frequent, low-intensity and patchily distributed (Murphy *et al.*, 2013). The eucalypt and mixed-species savanna may experience fewer fires than the related eucalypt open forest savanna due to the rocky soils and variable grass cover.

Geographical extent

The eucalypt and mixed-species savanna occurs patchily across the Tiwi Islands throughout the more common eucalypt open forest savanna (Woinarski *et al.*, 2000). Woodlands with *Eucalyptus* and *Corymbia* species are common across the Northern Territory (Wilson *et al.*, 1990; Bowman, Wilson and Woinarski, 1991). Vast expanses of tropical savanna span northern Australia (Fox *et al.*, 2001) and are common globally (Keith *et al.*, 2020, 2022).

Flora

Typically, canopy height and cover are 10-20m and 10-20% cover, respectively which is lower for the eucalypt and mixed-species savanna than for the eucalypt open forest savanna (Woinarski *et al.*, 2000; Woinarski, Brennan, Cowie, *et al.*, 2003). The floristic composition is characteristically heterogeneous. There are an extensive variety *Eucalyptus Corymbia* species in the canopy, including *Eucalyptus oligantha* (mantipungala), *E. alba* (white gum, pintampunga), *Corymbia bleeseri* (bloodwood, tuwaninga), *C. polycarpa* (bloodwood, wurringilaka), *C. ptychocarpa* (swamp bloodwood, pawlika), *C. latifolia* (round-leaved bloodwood, mintalima/kiripayi), *C. disjuncta* (wurritjinga), *C. confertiflora* (broad-leaved carbeen, wurritjinga), and *C. bella* (ghost gum, wuranungapingala/ pintampunga). Other canopy species can include *Verticordia cunninghamii* (Tree featherflower), *Syzygium suborbiculare* (red bush apple, pinyawini), and *Lophostemon lactifluus* (swamp mahogany, pulumutuma) (Brocklehurst and Edmeades, 1998; Woinarski *et al.*, 2000; Woinarski, Brennan, Cowie, *et al.*, 2003). This heterogeneity is different to the eucalypt open forest savanna ecosystem, which only varies in composition between three to five key tree species.

The midstory may include *Acacia* spp., *Grevillea* spp., *Planchonia careya* (Cocky apple, kanuli), *Coelospermum reticulatum*, *Livistona humilis* (Sand palm, miparri), *Cycas armstrongii* (vulnerable$_{NT}$, minta), *Clerodendrum floribundum* (lolly bush), *Petalostigma pubescens* (quinine bush), *Terminalia ferdinandiana* (Billy goat plum, pirlamunga), and *Calytrix exstipulata* (pink turkey bush, murinyini) (Brocklehurst and Edmeades, 1998). The ground cover is low tussock grasses with variable species composition, including *Eriachne* spp., *Aristida* spp., *Sorghum* spp. (marakati), *Pseudopogonatherum* spp., and *Chrysopogon fallax* (pitarika) (Brocklehurst and Edmeades, 1998). The variety in structural forms and floristic composition indicates that this ecosystem type is multiple vegetation types. The eucalypt woodland defined by Woinarski et al. (2003) supports two species currently listed as data deficient, *Crotalaria sessiliflora* and *Mitrasacme inornate.*

Fauna

The eucalypt and mixed-species woodland savannas support the highest reptile species and ant species richness and abundance (Fensham and Woinarski, 1992; Andersen, Woinarski and Hoffmann, 2004) and more granivorous birds compared to the other ecosystems; however, there is a lower abundance and diversity of arboreal rodents and marsupials (Woinarski, 2004c). Small and medium-sized mammals are likely similar to eucalypt open forest savanna communities and utilise diverse resources from the variable plant species. Threatened species known to use similar savanna systems on the mainland of Australia include the pale field rat (*Rattus tunneyi*, wurruwataka) (Department of Environment, Parks and Water Security, 2021n), fawn antechinus (vulnerable$_{AUS}$, endangered$_{NT}$, *Antechinus bellus*) (Department of Environment, Parks and Water Security, 2021e) and yellow spotted monitor (vulnerable$_{NT}$, *Varanus panoptes*)(Department of Environment and Natural Resources, 2006b).

Potential threats

Tropical savannas are one of the most vulnerable ecosystems to minor environmental changes in Australia (Laurance *et al.*, 2011). Weed invasion is the biggest threat to Australian tropical savannas (Laurance *et al.*, 2011). Weeds outcompete native tussock grasses, notably the weedy hyptis (*Mesosphaerum suaveolens)*, and impact fire regimes (Woinarski, Brennan, Cowie, *et al.*, 2003). Similar to the eucalypt open forest savanna, inappropriate fire regimes with too frequent and high severity may degrade the ecosystem integrity through a change in species composition (Laurance *et al.*, 2011; Williams *et al.*, 2017). Wildfires may also increase in severity under climate change (Laurance *et al.*, 2011). Invasive animals also pose a substantial risk. The eucalypt and mixed-species savannas may also be grazed by feral ungulates, in particular buffalo (*Bubalus bubalis*). Grazing and the movement of buffalo would reduce grass biomass, spread weeds, trample seedlings, and hinder regeneration (Woinarski, Brennan, Cowie, *et al.*, 2003; Laurance *et al.*, 2011). Cat (*Felis catus*) predation may also impact the mammal, reptile and bird communities (Woinarski, 2004a; Davies *et al.*, 2017; Neave *et al.*, 2024). Clearing for development would reduce the total area of the eucalypt and mixed-species savanna and increase fragmentation, with resultant impacts on the dispersal and connectivity (Laurance *et al.*, 2011).

Table 9. Cross-reference of the eucalypt and mixed species savanna ecosystem to eight classification schemes spanning the global, national, state, and local levels.

Tiwi Islands ecosystem type	Global Ecosystem Typology ecosystem functional group (level 3)[1]	International Vegetation Classification formations (level 3)[2]	NVIS major vegetation group[3]	NVIS major vegetation sub-group[3]	Northern Territory vegetation map[4]	Northern Territory macrogroups[5]	Generalised vegetation types of the Tiwi Islands[6]	Tiwi Island vegetation map[7]
Eucalypt and mixed-species savanna	T4.2 Pyric tussock savanna	T3.a Tropical savanna	12. Tropical Eucalypt woodlands/grasslands	7. Tropical Eucalyptus open forests and woodlands with a tall annual grassy understory 8. Eucalyptus woodlands with a shrubby understorey 9. Eucalypt woodland with tussock grass understorey 19. Eucalyptus low open woodlands with tussock grass. 48. Eucalypt open woodland with grass understorey	9. *E. tetrodonta* (Stringybark), *E. miniata* (Darwin woolly butt), *C. blesseri* (Smooth-stemmed bloodwood) woodland with *Sorghum* grassland understorey. 18. *Corymbia papuana* (Ghost gum), *C. polycarpa* (Long-fruited bloodwood) woodland with grassland understorey.	6. Australian Broad-leaved Bloodwood *Corymbia foelscheana* Scleromorphic Woodland	1c: *Corymbia bleeseri* & *Eucalyptus tetrodonta* open forest/woodland with tussock grassland understorey 1d: *Lophostemon lactifluus*, *C. nesophila* & *C. ptychocarpa*, open forest/woodland with tussock grassland understorey 1f: *C. polycarpa* open-forest with open-grassland understorey 1g. *E. oligantha*, *Erythrophleum chlorostachys* open forest/woodland with *Chrysopogon fallax* tussock grassland understorey	Eucalypt woodland

[1] Keith, D. A., Ferrer-Paris, J. R., Nicholson, E., Bishop, M. J., Polidoro, B. A., Ramirez-Llodra, E., Tozer, M. G., Nel, J. L., Mac Nally, R., Gregr, E. J., Watermeyer, K. E., Essl, F., Faber-Langendoen, D., Franklin, J., Lehmann, C. E. R., Etter, A., Roux, D. J., Stark, J. S., Rowland, J. A., Brummitt, N.A., Fernandez-Arcaya, U.C., Suthers, I.M., Wiser, S.K., Donohue, I., Jackson, L.J., Pennington, R.T., Iliffe, T.M., Gerovasileiou, V., Giller, P., Robson, B.J., Pettorelli, N., Andrade, A., Lindgaard, A., Tahvanainen, T., Terauds, A., Chadwick, M.A., Murray, N.J., Moat, J., Pliscoff, P., Zager, I. and Kingsford, R. T. (2022). A function-based typology for Earth's ecosystems. *Nature*, *610*(7932), Article 7932. https://doi.org/10.1038/s41586-022-05318-4

[2] Faber-Langendoen, D., Keeler-Wolf, T., Meidinger, D., Tart, D., Hoagland, B., Josse, C., Navarro, G., Ponomarenko, S., Saucier, J.-P., Weakley, A., & Comer, P. (2014). EcoVeg: A new approach to vegetation description and classification. *Ecological Monographs*, *84*(4), 533–561. https://doi.org/10.1890/13-2334.1

[3] DCCEW. (2020). *National Vegetation Information System* (Version 6) [Computer software]. Australian Government. https://www.dcceew.gov.au/environment/land/native-vegetation/national-vegetation-information-system/data-products

[4] Wilson, B. A., Brocklehurst, P. S., Clark, M. J., & Dickonson, K. J. M. (1990). *Vegetation survey of the Northern Territory, Australia, 1990.* [Photos]. NT Map Shop.

[5] Hunter, J.T., Lewis, D., Addicott, E., Luxton, S., Cowie, I., Sparrow, B. and Leitch, E. (2022). A plot-based analysis of the vegetation of the Northern Territory, Australia: a first assessment within the International Vegetation Classification framework', *Vegetation Classification and Survey*, 3, pp. 161–174. Available at: https://doi.org/10.3897/VCS.83045.

[6] Brocklehurst, P., & Edmeades, B. (1998). Vegetation communities. In *The history and natural resources of the Tiwi Islands, Northern Territory*. Parks and Wildlife Commission of the Northern Territory.

[7] Woinarski, J. C. Z., Brennan, K., Cowie, I., Kerrigan, R., & Hempel, C. (2003). *Biodiversity conservation on the Tiwi Islands, Northern Territory: Part 1. Environments and plants*.

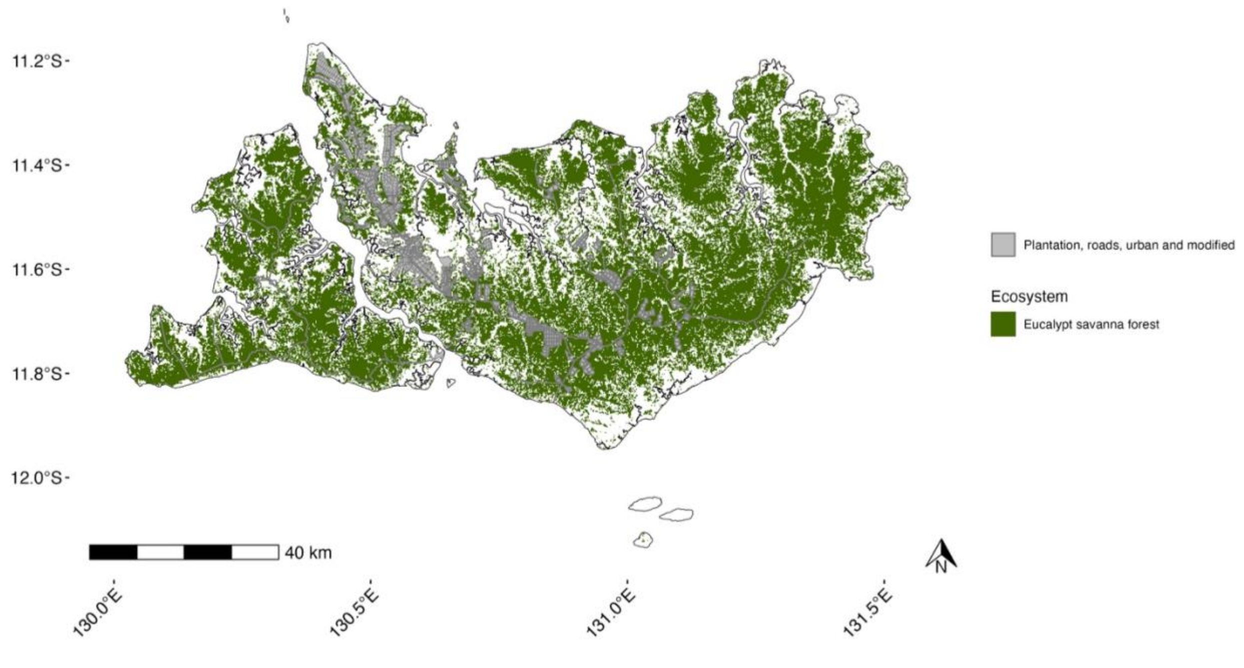


Figure 13. Map of the spatial distribution of the eucalypt savanna which is a combination of the eucalypt open forest savanna and eucalypt and mixed-species savanna ecosystems.

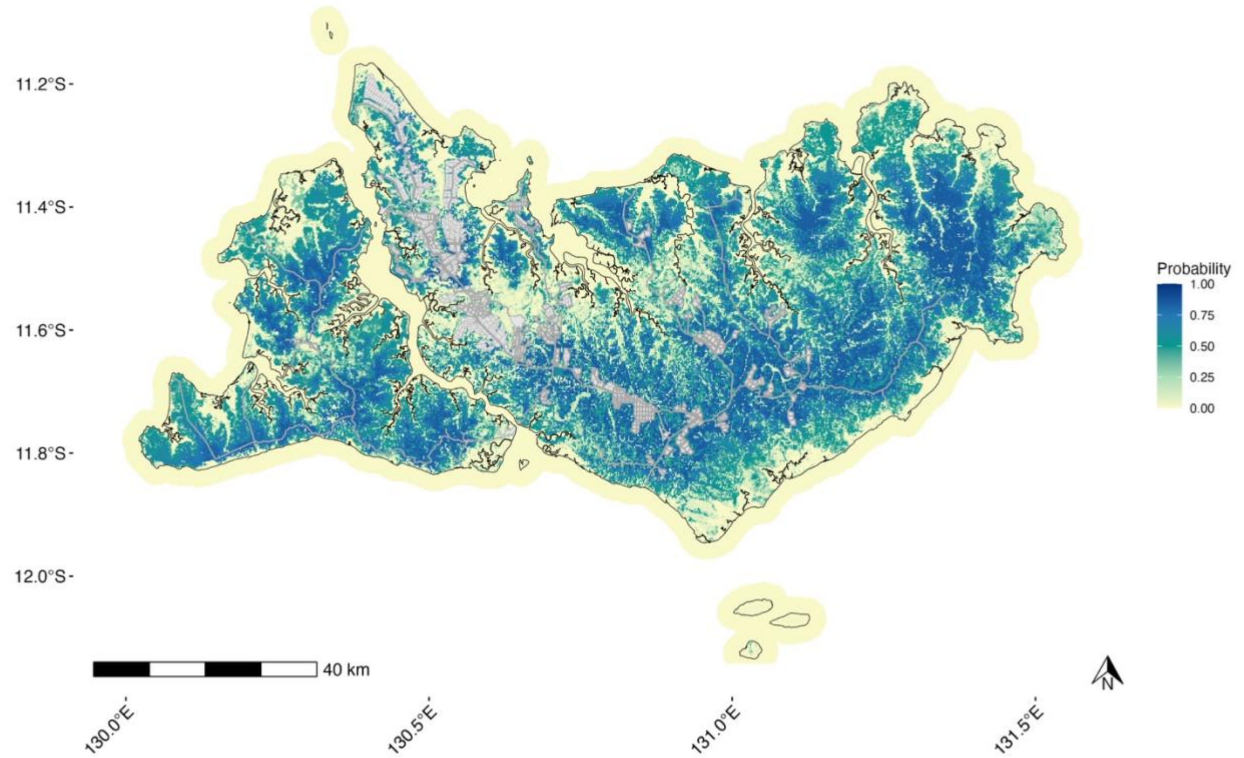


Figure 14. Map of the prediction probability for the extent of the eucalypt savanna which is a combination of the eucalypt open forest savanna and eucalypt and mixed-species savanna ecosystems

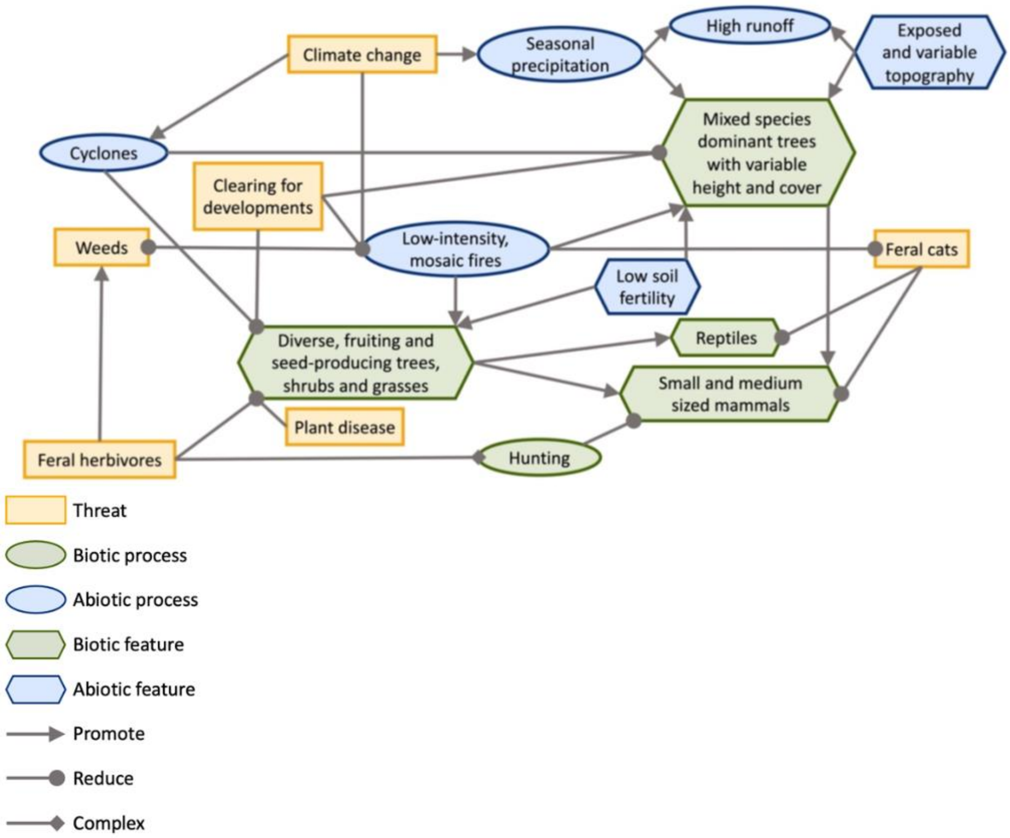


Figure 15. Cause-and-effect conceptual model based on the Red List of Ecosystem conceptual model structure for the eucalypt and mixed species savanna ecosystems.

Figure 16. Images of the eucalypt and mixed species savanna ecosystem on the Tiwi Islands, Australia which is characterised by a variable species composition in the canopy, over a tussock grass groundcover on multiple landforms and experiencing seasonal water deficient. Due to this variation, the ecosystem pictured above could be split further by soil moisture gradients and further into multiple vegetation types.

Treeless plains. Murinyini.

Ecosystem function

The treeless plains (murinyini in Tiwi language) is a unique and variable ecosystem. Soils are highly variable (Wilson and Fensham, 1994), potentially sandier, poorly drained, and less fertile than the surrounding savanna (Wells, van Cuylenburg and Dunlop, 1978; Wilson and Bowman, 1994; Wilson and Fensham, 1994). Soil properties and nutrients are likely important factors driving the distribution and function of the ecosystem, as identified for the ecosystem functional group 'T3.1 Seasonally dry tropical shrublands' (Keith *et al.*, 2020, 2022). The dominant flora varies with soil colour and texture (Wells, van Cuylenburg and Dunlop, 1978; Wilson and Fensham, 1994). The edaphic properties also interact with soil moisture. The ecosystem experiences seasonal waterlogging and drought, inhibiting the common eucalypt species present in the nearby eucalypt savanna and creating abrupt boundaries (Wilson and Bowman, 1994; Wilson and Fensham, 1994). The presence of sedges in the understorey suggests water availability, and standing water is common during the wet season in some areas (EcOz Environmental Consultants, 2021). The relationship of the shrublands to fire for the Tiwi Islands is less clear, although it appears highly variable and related to both soil moisture and prescribed fire.

Geographical extent

Previous analysis found that the shrublands cover 183 km^2 (~2.5%) of the Tiwi Islands over 11 large patches in a distinct latitudinal band (Wilson *et al.*, 1990; Wilson and Bowman, 1994; Woinarski *et al.*, 2000; Woinarski and Baker, 2002; Woinarski, Brennan, Cowie, *et al.*, 2003). Example locations are Rola plains and adjacent to plantations at Yapilika (Wilson and Bowman, 1994). In the Northern Territory more broadly, vegetation communities dominated by *Banksia dentata*, *Grevillea pteridifolia* or *Acacia* sp. occur in small patches driven by waterlogging (Wilson *et al.*, 1990; Wilson and Fensham, 1994; Fox *et al.*, 2001).

Flora

The shrublands exhibit a broad range of low and open structures (Wilson and Fensham, 1994; Hollingsworth *et al.*, 2006). In the Tiwi language, multiple of these characteristic floral species have the same name as the treeless plains ecosystem; 'Murinyini' (TLC *et al.*, 2001). Floristically, the shrublands are unique on the Tiwi Islands and highly variable. The canopy generally includes *Acacia difficilis*, *A. gonocarpa*, *A. latescens*, *Banksia dentata*, *Grevillea pteridifolia*, *Melaleuca viridiflora*, *Lophostemon lactifluus*, and *Syzygium eucalyptoides* (Wilson and Fensham, 1994; Brocklehurst and Edmeades, 1998). The understory is grass-dominated, with sedges common both during the wet season and in highly waterlogged sites (Wilson and Fensham, 1994). The treeless plains also supports one data-deficient species, *Stylidium tenerrimum*. Importantly, studies on the shrublands are aggregated towards western Melville Island and may misrepresent eastern Melville Island and Bathurst Island (Wilson and Fensham, 1994).

Fauna

Compared to other ecosystems, the shrublands support low bird species richness and abundance (Fensham and Woinarski, 1992). In other areas of the Northern Territory, the hooded robin *Melanodryas cucullata* occurs in *Acacia* woodlands, although the Tiwi Island endemic subspecies *Melanodryas cucullate melvillensis* (critically endangered$_{AUS, NT}$) is presumed extinct (Woinarski, Brennan, Hempel, *et al.*, 2003; Department of Environment, Parks and Water Security, 2021g). Other threatened species potentially associated with the shrublands include the Tiwi masked owl (endangered$_{AUS, NT}$, *Tyto novaehollandiae melvillensis*) and the Horsfield's bushlark (vulnerable$_{AUS, NT}$, *Mirafra javanica melvillensis*) (Department of Environment, Parks and Water Security, 2021h, 2021j). There are also many data-deficient animals which may utilize the treeless plains as well as other ecosystems (Woinarski, Brennan, Hempel, *et al.*, 2003)

Potential threats

Exotic plants are among tropical Australia's greatest threats (Leishman *et al.*, 2017). For the Tiwi Islands and tropical savannas, gamba grass (*Andropogon gayanus)* and mission grass (*Cenchrus polystachion*) post substantial potential risks to any grassy ecosystem through positive feedback loops with high frequency and severity fire (Woinarski, Hadden, Hicks, *et al.*, 2003). Historical clearing during the 1960s and 1980s resulted in a loss of 10% of the total area of treeless plains (TLC *et al.*, 2001). The treeless plains occur naturally in a fragmented distribution (Wilson *et al.*, 1990; Woinarski *et al.*, 2000). Further clearing may increase the fragmentation and hinder animal and plant dispersal. Given the importance of soil moisture in driving the plant community structure and inhibiting the growth of savanna trees, any development that involves water extraction may also negatively impact the treeless plains. Another threat to the treeless plains ecosystem is the lack of accurate mapping to monitor the distribution and health of the vegetation types.

Table 10. Cross-reference of the mixed species shrubland and woodlands ecosystem to eight classification schemes spanning the global, national, state and regional scales.

Tiwi Islands ecosystem type	Global Ecosystem Typology ecosystem functional group (level 3)[1]	International Vegetation Classification formations (level 3)[2]	NVIS major vegetation group[3]	NVIS major vegetation sub-group[3]	Northern Territory vegetation map[4]	Northern Territory macrogroups[5]	Generalised vegetation types of the Tiwi Islands[6]	Tiwi Island vegetation map[7]
Treeless plains	T3.1 Seasonally dry tropical shrubland	T3.b2 Seasonally dry tropical shrubland	16. Acacia shrublands	21. Other *Acacia* tall open shrublands and [tall] shrublands 24. *Acacia* (+/- low) open woodlands and	47. *Acacia* open-shrubland with *Sorghum* grassland understorey.	MG3. Australian Paperbark *Melaleuca viridiflora*– Long-fruited Bloodwood *Corymbia polycarpa* Forest and Woodland - (e.g. species *M. viridiflora*, *Grevillea pteridifolia*, *C.*	5: Sparsely wooded plains 5a: *Acacia* open-shrub land 5b: *Grevillea pteridifolia* low woodland	Treeless plains

	sparse shrublands (+/-) tussock grass	*polycarpa*, *Lophostemon lactifluus*, *M. nervosa*)	5c: *L. lactifluus* low woodland
17. Other shrublands	28. Low closed forest or tall closed shrublands (including *Acacia*, *Melaleuca* and *Banksia*)		5d: *Acacia* shrub land 5e: *Banksia* low woodland 1h: *Grevillea pteridifolia* low open-woodland/tall shrubland with *Eriachne burkitti* grassland understorey
	49. *Melaleuca* shrublands and open shrublands.		
31. Other open woodlands	79. Other open woodlands		

[1] Keith, D. A., Ferrer-Paris, J. R., Nicholson, E., Bishop, M. J., Polidoro, B. A., Ramirez-Llodra, E., Tozer, M. G., Nel, J. L., Mac Nally, R., Gregr, E. J., Watermeyer, K. E., Essl, F., Faber-Langendoen, D., Franklin, J., Lehmann, C. E. R., Etter, A., Roux, D. J., Stark, J. S., Rowland, J. A., Brummitt, N.A., Fernandez-Arcaya, U.C., Suthers, I.M., Wiser, S.K., Donohue, I., Jackson, L.J., Pennington, R.T., Iliffe, T.M., Gerovasileiou, V., Giller, P., Robson, B.J., Pettorelli, N., Andrade, A., Lindgaard, A., Tahvanainen, T., Terauds, A., Chadwick, M.A., Murray, N.J., Moat, J., Pliscoff, P., Zager, I. and Kingsford, R. T. (2022). A function-based typology for Earth's ecosystems. *Nature*, *610*(7932), Article 7932. https://doi.org/10.1038/s41586-022-05318-4

[2] Faber-Langendoen, D., Keeler-Wolf, T., Meidinger, D., Tart, D., Hoagland, B., Josse, C., Navarro, G., Ponomarenko, S., Saucier, J.-P., Weakley, A., & Comer, P. (2014). EcoVeg: A new approach to vegetation description and classification. *Ecological Monographs*, *84*(4), 533–561. https://doi.org/10.1890/13-2334.1

[3] DCCEW. (2020). *National Vegetation Information System* (Version 6) [Computer software]. Australian Government. https://www.dcceew.gov.au/environment/land/native-vegetation/national-vegetation-information-system/data-products

[4] Wilson, B. A., Brocklehurst, P. S., Clark, M. J., & Dickonson, K. J. M. (1990). *Vegetation survey ofthe Northern Territory, Australia, 1990.* [Photos]. NT Map Shop.

[5] Hunter, J.T., Lewis, D., Addicott, E., Luxton, S., Cowie, I., Sparrow, B. and Leitch, E. (2022). A plot-based analysis of the vegetation of the Northern Territory, Australia: a first assessment within the International Vegetation Classification framework', *Vegetation Classification and Survey*, 3, pp. 161–174. Available at: https://doi.org/10.3897/VCS.83045.

[6] Brocklehurst, P., & Edmeades, B. (1998). Vegetation communities. In *The history and natural resources of the Tiwi Islands, Northern Territory.* Parks and Wildlife Commission of the Northern Territory.

[7] Woinarski, J. C. Z., Brennan, K., Cowie, I., Kerrigan, R., & Hempel, C. (2003). *Biodiversity conservation on the Tiwi Islands, Northern Territory: Part 1. Environments and plants*.

[8] Wilson, B.A. and Fensham, R.J. (1994) 'A comparison of classification systems for the conservation of sparsely wooded plains on Melville Island, Northern Australia', *Australian Geographer*, 25(1), pp. 18–31. Available at: https://doi.org/10.1080/00049189408703095.

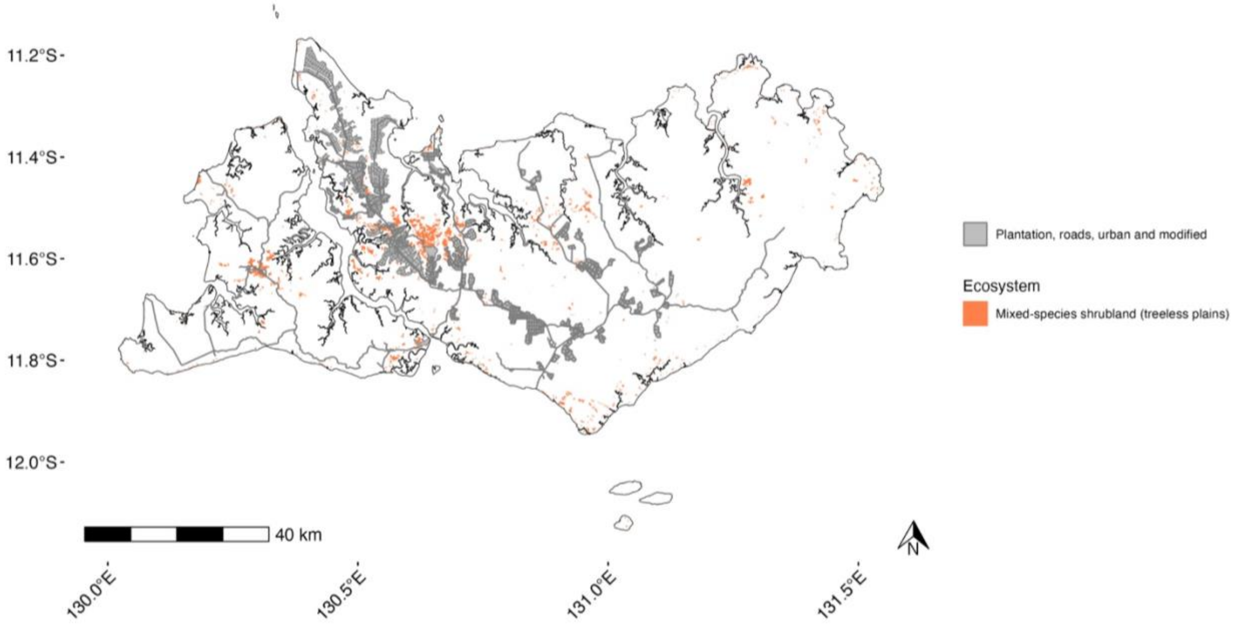


Figure 17. Map of the spatial distribution of the 'treeless plains ecosystem on the Tiwi Islands, Australia.

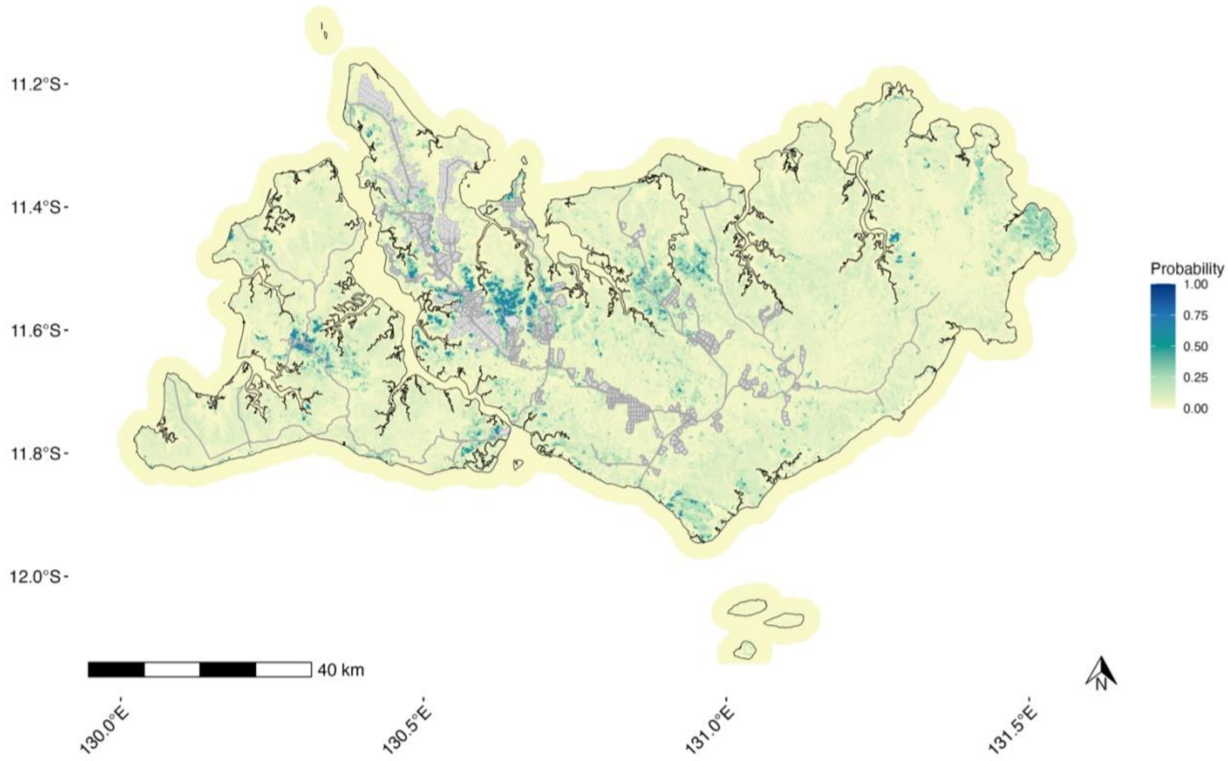


Figure 18. The prediction probability of the treeless plains ecosystem on the Tiwi Islands, Australia from the random classification model.

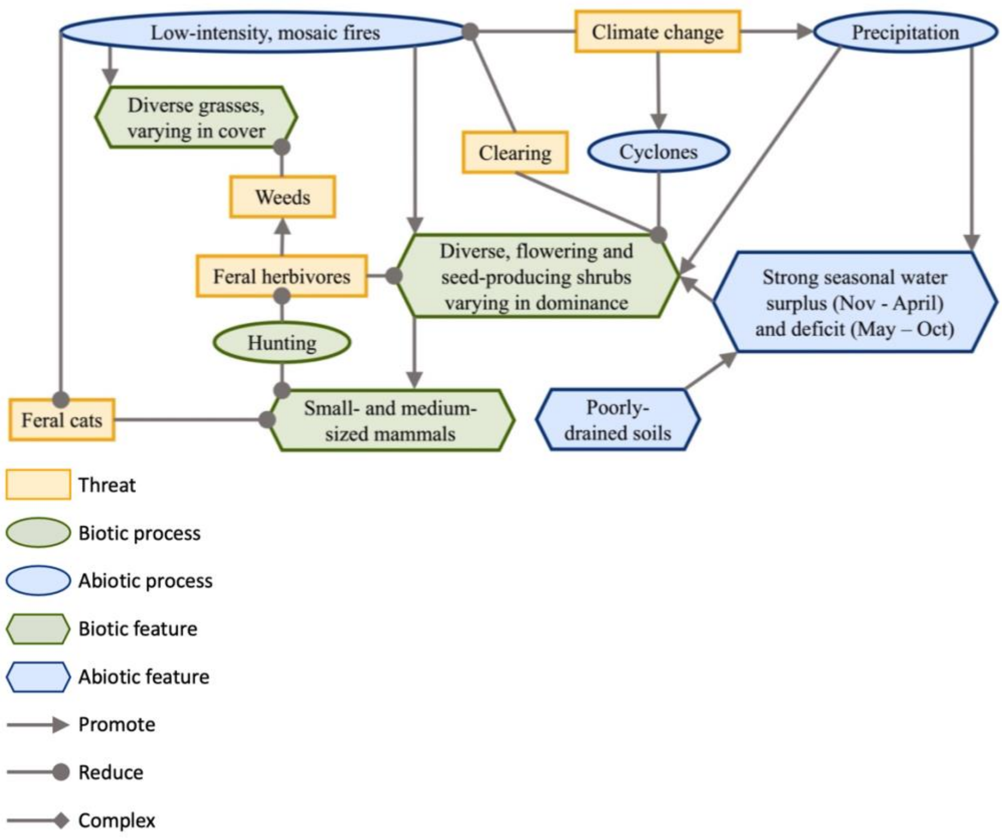


Figure 19. Cause-and-effect conceptual model based on the Red List of Ecosystem conceptual model structure for the treeless plains ecosystem.

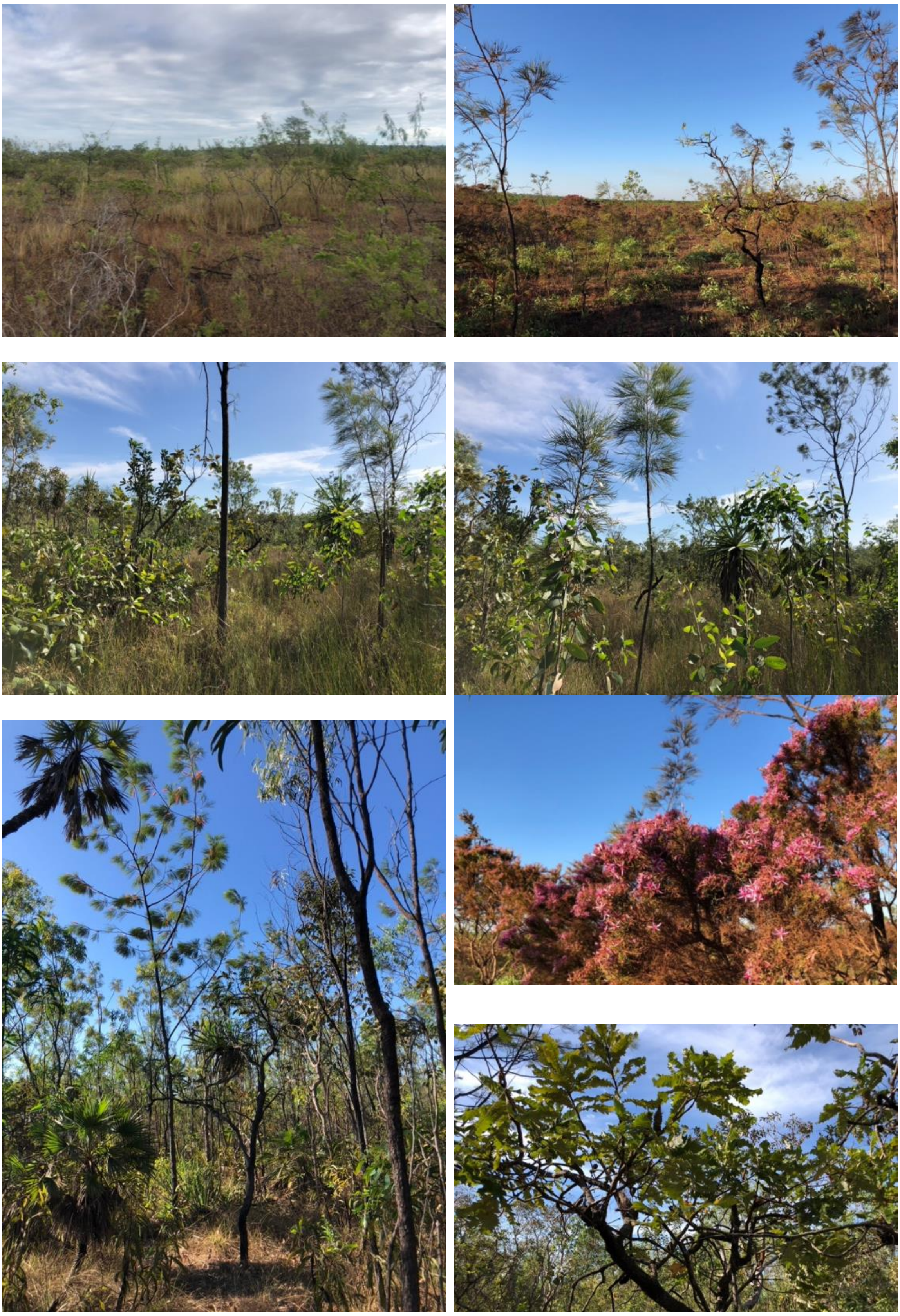


Figure 20. Images of the treeless plains ecosystem on the Tiwi Islands, Australia.

Wet rainforest. Yawurlama.

Ecosystem function

Wet rainforests (yawurlama and yawurlawini in Tiwi language) are tall, diverse, mostly evergreen and closed-canopy forests on perennially moist substrates (Metcalfe and Green, 2017; Department of Environment and Natural Resources, 2018b; Keith *et al.*, 2022). Soil moisture is permanently availability with freshwater permeating from springs, creeks, streams and drainage lines (Metcalfe and Green, 2017; Keith *et al.*, 2020). Edaphic properties compound the water availability rather than drive the distribution of rainforests (Department of Environment and Natural Resources, 2018b). Permanent freshwater availability is a key ecological driver distinguishing wet and dry rainforest expressions on the Tiwi Islands (Russell-Smith, 1991; Bowman, 1992; Hollingsworth et al., 2006). While the word in Tiwi language "yawurlama" relates to both wet and dry rainforest, the difference between the two ecosystems is recognised by Tiwi people from our research with Colin Kerinaiua describing the species differences and Bernard Tipiloura describing the ecosystem services they provide to Tiwi people. Soil moisture appears to restrict the distribution of the rainforest, creating an archipelago of small discrete patches with large variations in sizes (Metcalfe and Green, 2017; Department of Environment and Natural Resources, 2018b). Internally, the wet rainforests maintain a stable and humid microclimate (Keith *et al.*, 2020). Fire mediates rainforest boundaries (Banfai and Bowman, 2006; Department of Environment and Natural Resources, 2018b). Internally, rainforests experience little to no fire and as such, provide refuge in the fire-prone tropical savanna landscape (Bowman, 1992). Some fires that begin outside the rainforest during dry periods, such as during severe droughts, may penetrate the rainforest ecosystem (Bowman, 1992; Metcalfe and Green, 2017). *Melaleuca leucadendra* trees and *Pandanus spiralis* grow along permanent freshwater streams, forming the riparian expression of the rainforest ecosystem (Petty, Douglas and Ferdinands, 2007). The riparian rainforests of the Tiwi Islands have been 1) analysed separately from spring-fed rainforests (e.g. Russell-Smith, 1991), 2) acknowledged as different yet analysed together (e.g. Hollingsworth et al., 2006) or 3) combined (e.g. Woinarski *et al.*, 2003) due to the narrow dimensions and floristic heterogeneity (Woinarski, Brennan, Cowie, *et al.*, 2003; Woinarski, 2004c). In Tiwi, "kukuni" for freshwater and "makaringa" for stream were suggested to differentiate the spring-fed and the riparian rainforest expressions by Bernard Tipiloura and during the database meeting.

Geographic extent

Wet rainforests are extensive and well-developed on the Tiwi Islands, particularly in the highest rainfall areas of north-western Melville Island (Russell-Smith and Lee, 1992; Liddle and Elliott, 2008). Even within the Tiwi-Cobourg bioregion, wet rainforests on the Tiwi Islands are high in number, area, and species diversity (Brocklehurst and Edmeades, 1998; Woinarski and Baker, 2002). The total number of rainforest patches on the Tiwi Islands was estimated to be 1261, of which 302 patches occur on Bathurst Island and 959 on Melville Island (Woinarski *et al.*, 2000). In the Northern Territory, wet and dry monsoonal rainforests span from the Tiwi Islands to Tennant Creek (Department of Environment and Natural Resources, 2018b). Wet rainforests are present throughout northern Australia, particularly on Cape York Peninsula, the Wet Tropics of northern Queensland and the Kimberley in Western Australia (Metcalfe and Green, 2017) and their distribution reflects a clear soil moisture gradient (Metcalfe and Green, 2017). In the Northern Territory and Western Australia, wet rainforests are often called monsoon vine forests (Metcalfe and Green, 2017).

Flora

Wet rainforests tend to have a high floristic and structural diversity across the Northern Territory and Australia (Metcalfe and Green, 2017; Department of Environment and Natural Resources, 2018b). The species-rich canopy reaches 10 – 25 m in height with 50-90% cover with evergreen trees and palms, while ferns and leaf litter dominate the humic-rich soils (Russell-Smith, 1991; Bowman, 1992; Hollingsworth *et al.*, 2006; Department of Environment and Natural Resources, 2018b). Dominant tree species include *Calophyllum soulattri* (pampiyaka), *Syzygium minutuliflorum*, *Melicope elleryana*, *Utania racemosa* (turukwanga), *Hydriastele wendlandiana* (kentia palm, paliwuni), *Dicranopteris linearis* (tipurrukurluwa), *Blechnum orientale* and *Stenochlaena palustris* (Russell-Smith, 1991; Russell-Smith and Bowman, 1992; TLC *et al.*, 2001). In Australia, wet and tropical rainforests tend to support many endemic species which is true on the Tiwi Islands (Metcalfe and Green, 2017). Wet rainforests on the Tiwi Islands sustain numerous threatened and endemic plant species, including the critically endangered *Elaeocarpus miegei*, four endangered species and nine vulnerable species (Woinarski, Brennan, Cowie, *et al.*, 2003; Liddle and Elliott, 2008). Rainforest plants provide important bush medicines for Tiwi people, including *Alphitonia excelsa* (jikiringi, soap bush) (TLC *et al.,* 2001; Thompson *et al.*, 2019).

Fauna

The abundant resources support a diverse faunal community and extended trophic food chains (Keith *et al.*, 2022). Wet rainforests tend to support a high diversity of invertebrates (Keith *et al.*, 2020) with many unique and endemic ant species on the Tiwi Islands (Andersen *et al.*, 2012). In the Northern Territory more broadly, rainforests are important habitat for ant species with many rainforest specialists (Reichel and Andersen, 1996). Frugivorous and nectarivorous birds and mammals are critical in pollination and seed dispersal (Fensham and Woinarski, 1992; Department of Environment and Natural Resources, 2018b; Keith *et al.*, 2020). Common birds include the dusky honeyeater (*Myzomela obscura*), Torresian imperial pigeon (*Ducula spilorrhoa*), little shrike-thrush (*Colluricincla megarhyncha*), and bats include black flying-fox (*Pteropus alecto*) and Arnhem long-eared bat (*Nyctophilus arnhemensis*) (Fensham and Woinarski, 1992). Overall, rainforests support similar species compositions to the surrounding savanna and mangrove landscape (Fensham and Woinarski, 1992; Gambold and Woinarski, 1993; Andersen *et al.*, 2012), with a few unique species to the Tiwi Islands but also the absence of common species from the mainland (Fensham and Woinarski, 1992; Andersen *et al.*, 2012). For reptiles and amphibians, *Sphenophryne adelphe* (frog), *Lygisaurus macfarlani* (skink) and carpet python (*Morelia spilota*, yilinga) are common (Fensham and Woinarski, 1992). Three threatened species inhabit rainforest patches: the Tiwi Island treesnail *Amphidromus cognatus* (vulnerable$_{NT}$) (Department of Environment, Parks and Water Security, 2021q), the atlas moth (*Attacus wardi*, vulnerable$_{NT}$)(Department of Environment, Parks and Water Security, 2021a) and the Tiwi masked owl (*Tyto novaehollandiae melvillensis*, endangered$_{AUS, NT}$)(Department of Environment, Parks and Water Security, 2021j).

Potential threats

Wet rainforests face multiple interacting threats. Invasive species are particularly detrimental, including feral animals, invasive ants and weeds (Metcalfe and Green, 2017; Department of Environment and Natural Resources, 2018b). In the Northern Territory, 22% of rainforests in the Northern Territory were infested with weeds in 1992 (Russell-Smith and Bowman, 1992). No single weed dominates the infestations; common weeds include *Lantana camara, Hyptis suaveolens, Senna occidentalis, S. obtusifolia, Sida cordifolia, S. acuta, Andropogon gayanus* (gamba grass), *Cenchrus polystachios* (mission grass), *Passiflora foetida* (Russell-Smith and Bowman, 1992; Liddle and Elliott, 2008; Metcalfe and Green, 2017). In Kakadu National Park, *Hyptis suaveolens* invasion into wet rainforests was related to recent fire disturbance (Braithwaite *et al.*, 1984). Feral herbivores, particularly water buffalo (*Bubalus bubalis*) and wild pigs (*Sus scrofa*), physically damage plants, inhibit regeneration and introduce weeds into rainforest through uprooting, rubbing, wallowing, and trampling (Braithwaite *et al.*, 1984; Liddle and Elliott, 2008; EcOz Environmental Consultants, 2021). Buffalo may also contribute to soil compaction, which impacts the hydrology of wet rainforests (Braithwaite *et al.*, 1984). Wet rainforests are affected by buffalo more than other ecosystem types (Braithwaite *et al.*, 1984), with damage recorded across the Northern Territory and on the Tiwi Islands (Russell-Smith and Bowman, 1992). *Acacia mangium* germinated from plantations, termed 'wildlings', are an emerging issue on the Tiwi Islands and have been recorded in rainforests (EcOz Environmental Consultants, 2021). The extent of the *A. mangium* distribution is difficult to ascertain due to the remote nature of the rainforest patches and limited access. Exotic ant species are also possible, although so far, they have been recorded in very low numbers at specific locations (Andersen *et al.*, 2012). The reliance of wet rainforests on groundwater renders the rainforest patches vulnerable to drier climatic conditions, the diminishing recharge of aquifers, and groundwater removal for developments (Braithwaite *et al.*, 1984; Liddle and Elliott, 2008). Water stress and drier conditions may exacerbate the fire susceptibility (Braithwaite *et al.*, 1984). Rainforests are highly sensitive to intense wildfires (Barrow *et al.*, 1993; Liddle and Elliott, 2008; Department of Environment and Natural Resources, 2018b). High frequency and severity fires risk destroying rainforest patches, either rapidly or slowly, through the continued erosion of the patch edges (Russell-Smith and Bowman, 1992). Wet rainforests display a naturally fragmented distribution. Further fragmentation may inhibit the movement of the frugivore species, which provide important pollination and seed dispersal services (Liddle and Elliott, 2008; Metcalfe and Green, 2017; Department of Environment and Natural Resources, 2018b). Historically, clearing was a significant threat to rainforests around Australia (Metcalfe and Green, 2017).

Table 11. Cross-reference of the wet rainforest ecosystem to eight classification schemes spanning the global, national, state, and regional scales.

Tiwi Islands ecosystem type	Global Ecosystem Typology ecosystem functional group (level 3)[1]	International Vegetation Classification formations (level 3)[2]	NVIS major vegetation group[3]	NVIS major vegetation sub-group[3]	Northern Territory vegetation map[4]	Northern Territory macrogroups[5]	Generalised vegetation types of the Tiwi Islands[6]	Tiwi Island vegetation map[7]	NT rainforests[8]
Wet rainforest	T1.1 Tropical/subtropical lowland rainforest	T1.a1 Tropical lowland rainforest	1. Rainforests and vine thickets.	62. Dry rainforest or vine thicket	1. Mixed species closed-forest (Monsoon vine thicket)	1. Australasian & East Malesian Dry Forest	4: Monsoon vine-forests	Wet rainforest	5. Edaphically complex forests
							4b: 'Wet' monsoon forests		3. Perennially moist substrates

[1] Keith, D. A., Ferrer-Paris, J. R., Nicholson, E., Bishop, M. J., Polidoro, B. A., Ramirez-Llodra, E., Tozer, M. G., Nel, J. L., Mac Nally, R., Gregr, E. J., Watermeyer, K. E., Essl, F., Faber-Langendoen, D., Franklin, J., Lehmann, C. E. R., Etter, A., Roux, D. J., Stark, J. S., Rowland, J. A., Brummitt, N.A., Fernandez-Arcaya, U.C., Suthers, I.M., Wiser, S.K., Donohue, I., Jackson, L.J., Pennington, R.T., Iliffe, T.M., Gerovasileiou, V., Giller, P., Robson, B.J., Pettorelli, N., Andrade, A., Lindgaard, A., Tahvanainen, T., Terauds, A., Chadwick, M.A., Murray, N.J., Moat, J., Pliscoff, P., Zager, I. and Kingsford, R. T. (2022). A function-based typology for Earth's ecosystems. *Nature*, *610*(7932), Article 7932. https://doi.org/10.1038/s41586-022-05318-4

[2] Faber-Langendoen, D., Keeler-Wolf, T., Meidinger, D., Tart, D., Hoagland, B., Josse, C., Navarro, G., Ponomarenko, S., Saucier, J.-P., Weakley, A., & Comer, P. (2014). EcoVeg: A new approach to vegetation description and classification. *Ecological Monographs*, *84*(4), 533–561. https://doi.org/10.1890/13-2334.1

[3] DCCEW. (2020). *National Vegetation Information System* (Version 6) [Computer software]. Australian Government. https://www.dcceew.gov.au/environment/land/native-vegetation/national-vegetation-information-system/data-products

[4] Wilson, B. A., Brocklehurst, P. S., Clark, M. J., & Dickonson, K. J. M. (1990). *Vegetation survey of the Northern Territory, Australia, 1990.* [Photos]. NT Map Shop.

[5] Hunter, J.T., Lewis, D., Addicott, E., Luxton, S., Cowie, I., Sparrow, B. and Leitch, E. (2022). A plot-based analysis of the vegetation of the Northern Territory, Australia: a first assessment within the International Vegetation Classification framework', *Vegetation Classification and Survey*, 3, pp. 161–174. Available at: https://doi.org/10.3897/VCS.83045.

[6] Brocklehurst, P., & Edmeades, B. (1998). Vegetation communities. In *The history and natural resources of the Tiwi Islands, Northern Territory.* Parks and Wildlife Commission of the Northern Territory.

[7] Woinarski, J. C. Z., Brennan, K., Cowie, I., Kerrigan, R., & Hempel, C. (2003). *Biodiversity conservation on the Tiwi Islands, Northern Territory: Part 1. Environments and plants*.

[8] Russell-Smith, J. (1991) 'Classification, species richness, and environmental relations of monsoon rain forest in northern Australia', *Journal of Vegetation Science*, *2*(2), 259–278. https://doi.org/10.2307/3235959

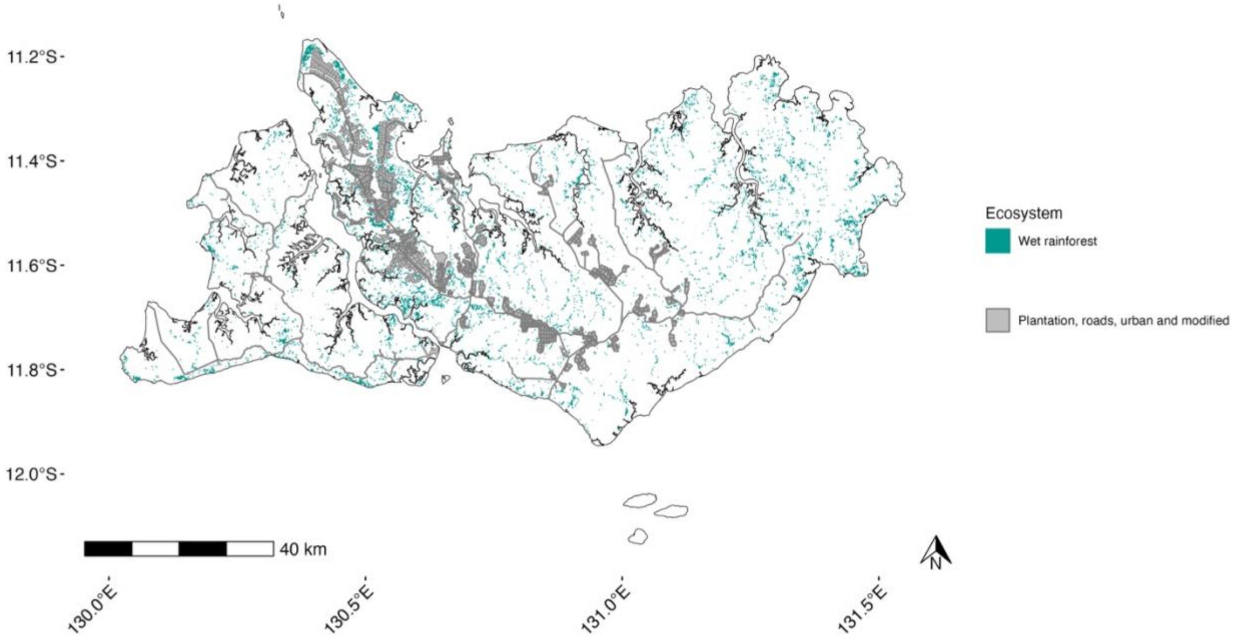


Figure 21. Map of the distribution of the wet rainforest ecosystem on the Tiwi Islands, Australia.

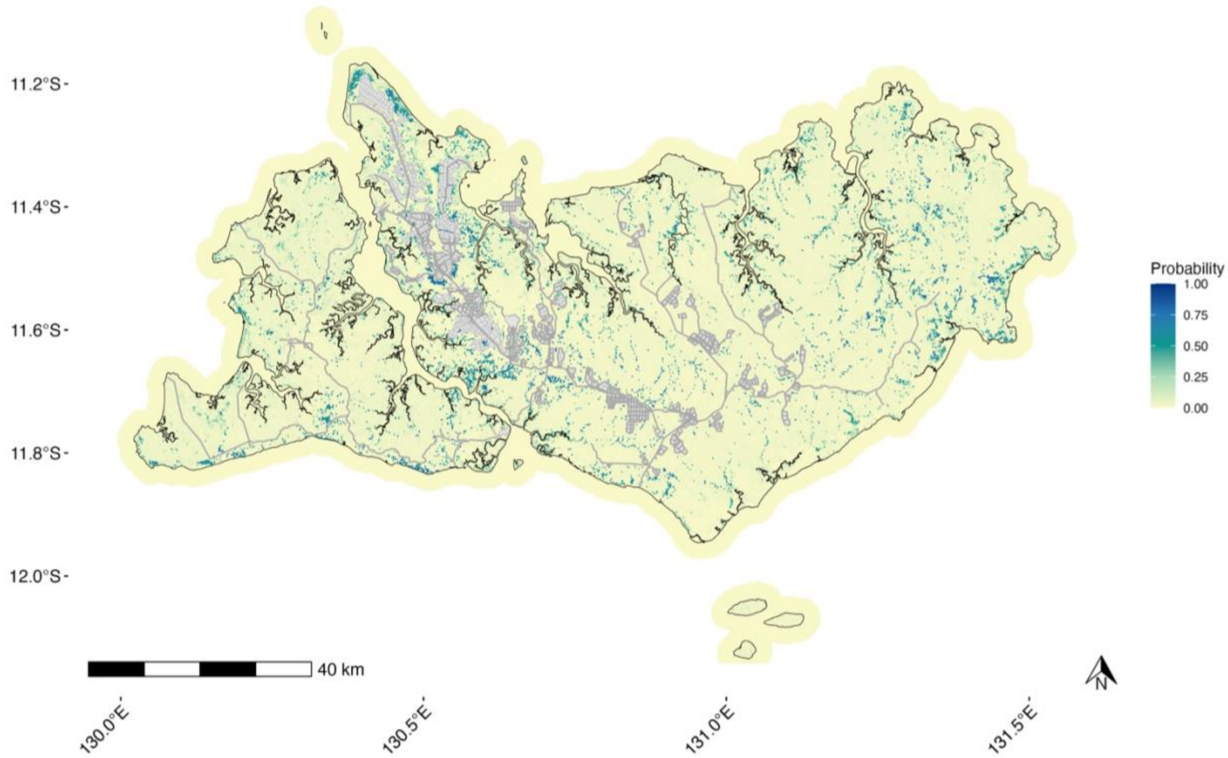


Figure 22. The prediction probability of the wet rainforest ecosystem on the Tiwi Islands, Australia from the random classification model.

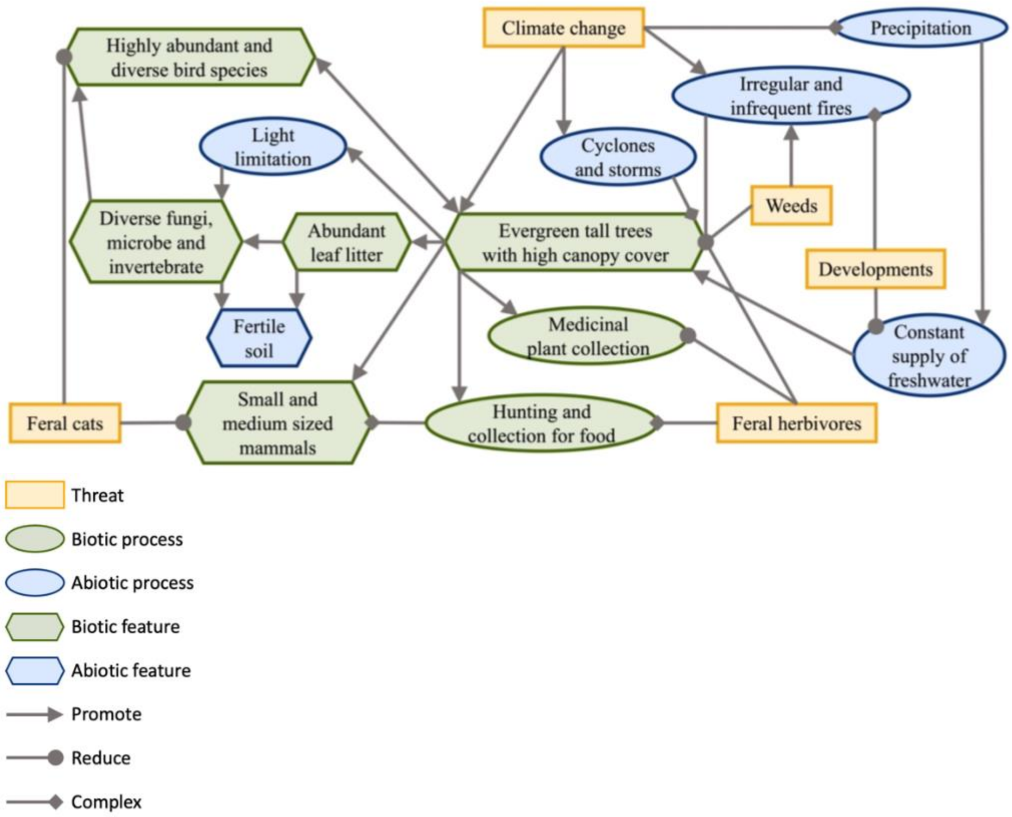


Figure 23. Cause-and-effect conceptual model based on the Red List of Ecosystem conceptual model structure for the wet rainforest ecosystem.

Figure 24. Photographs of the wet rainforest ecosystem on the Tiwi Islands, Australia. Wet rainforests include spring and riparian zones.

Dry rainforest and vine thicket. Yawurlama.

Ecosystem function

Dry rainforests (yawurlama in Tiwi language) are tall forests with evergreen to deciduous canopies on seasonally dry substrate (Russell-Smith, 1991; Woinarski *et al.*, 2000; Metcalfe and Green, 2017; Keith *et al.*, 2020). Unlike wet rainforests, dry rainforests tolerate seasonal drought periods during the dry season with no consistent freshwater input, similar to the surrounding savanna (Russell-Smith, 1991; Bowman, 1992; Metcalfe and Green, 2017; Department of Environment and Natural Resources, 2018b; Keith *et al.*, 2020). However, unlike the tropical savanna, fire is rare in the dry rainforests (Keith and Tozer, 2017). The lack of fire is likely due to topographical protection (Bowman, 1992) or rocky substrates (Metcalfe and Green, 2017). Regular fires in the abutting savanna create narrow or non-existent ecotones between the dry rainforest and the savanna (Bowman, 1992). Soils are well drained but highly variable in depth, texture and nutrients, but are unlikely to be a limiting environmental factor (Russell-Smith, 1991; Bowman, 1992). Dry rainforests occur in discontinuous patches (Metcalfe and Green, 2017), although the size of the patch can vary greatly (Russell-Smith, 1991; Department of Environment and Natural Resources, 2018b). The dry rainforest patches are typically larger than the spring rainforests (Woinarski *et al.*, 2000). Even though there did not appear to be a specific name for dry rainforests compared to wet rainforest, Tiwi knowledge holders described the different properties of the two types of rainforest. The adjective ‘yartupwarri’ placed before the name ‘yawurlama’ was suggested by Bernard Tipiloura; ‘yartupwarri’ refers to “ground that is dried out or almost dry” in the Tiwi dictionary (TLC *et al.*, 2001). Dry rainforests traditionally supplied many ecosystem services for Tiwi people (TLC *et al.*, 2001). Dry rainforests often occur in proximity to coastal ecosystems at the lee faces of sand dunes, floodplain margins, and the periphery of mangroves where the salt water creates abrupt boundaries (Fensham and Woinarski, 1992; Brocklehurst and Edmeades, 1998).

Geographic extent

On the Tiwi Islands, dry rainforests are extensive in the south-west of Bathurst Island on Jikilaruwu clan lands (Woinarski *et al.*, 2000), near the north coast of north-western Melville Island (Wilson *et al.*, 1990), and on the fore-dunes at Wangiti (Fensham, 1993). In the Northern Territory, wet and dry monsoonal rainforest span from the Tiwi Islands to Tennant Creek and often occur close to the coast (Wilson *et al.*, 1990; Russell-Smith, 1991; Brocklehurst and Edmeades, 1998; Department of Environment and Natural Resources, 2018b). More broadly, dry rainforest and vine thickets occur around Australia (Metcalfe and Green, 2017) and globally, with extensive areas in South America (Miles *et al.*, 2006; Keith *et al.*, 2022).

Flora

Vines and thickets are unique in this ecosystem compared to other ecosystems on the Tiwi Islands. The vines and thickets create a dense undergrowth and contributes to the overall high floristic diversity. Common vines are *Flagellaria indica* (mawunkati/mawunkatinga), and *Smilax australis* (austral sarsaparilla, Turukwanga). The dry rainforest vegetation types vary in the species composition, structure, and deciduous canopy (Russell-Smith, 1991; Brocklehurst and Edmeades, 1998). The dry rainforest can vary from tall forests up to 15 m high to thickets from 4 to 10 m tall, and from a fully to semi deciduous canopy(Russell-Smith, 1991; Brocklehurst and Edmeades, 1998). Distinctive species in the dry rainforest and vine thickets include *Glochidium xerocarpum* (pin flower tree), *Mallotus nesophilus* (yellow ball flower), *Sterculia quadrifida* (peanut tree/bush peanut, malikini/wurranyini), *Adenia heterophylla* (lacewing vine), *Capparis sepiaria*, *Croton habrophyllus*, *Drypetes deplanchei* (karpilitu), *Ixora timorensis*, *Sersalisia sericea* (murinyi), *Strychnos lucida*, *Diospyros calycantha* (cape ebony), *Litsea glutinosa*, *Cupaniopsis anacardioidse* and *Monoon australe*

(Russell-Smith, 1991; Fensham and Woinarski, 1992; Brocklehurst and Edmeades, 1998; Woinarski, Brennan, Cowie, *et al.*, 2003). Threatened plants include the vulnerable *Hoya australis* subsp. *oramicola* (vulnerable$_{NT}$, $_{AUS,}$ kulipiyawuni) and *Luisia corrugata* (vulnerable$_{NT}$, Luisia orchid) (Liddle, Gibbons and Taylor, 2008). Rainforests also support six data-deficient species (Woinarski, Brennan, Cowie, *et al.*, 2003). Dry rainforests also supply medicines from *Alphitonia excelsa* (jikiringi, soap bush) and *Ficus sp.* (tokapungna) (Thompson *et al.*, 2019).

Fauna

Similar species composition of mammals, birds, reptiles, ants and frogs are supported in rainforest patches (either wet or dry) and the surrounding savanna, mangroves and *Melaleuca* forests, as well as in other rainforests in the Northern Territory (Fensham and Woinarski, 1992; Gambold and Woinarski, 1993; Andersen *et al.*, 2012). Dry rainforests support unique species of ants compared to the wetter rainforest ecosystems on the Tiwi Islands (Andersen *et al.*, 2012). No mammal is restricted to rainforest patches (Menkhorst and Woinarski, 1992). Mammals, reptiles and amphibians appear to obtain specific resources from rainforest patches, such as fruits, tubers and seeds for food, or canopy cover for temperature regulation (Fensham and Woinarski, 1992; Gambold and Woinarski, 1993). The bird species are diverse, potentially due to the proximity to mangroves, with abundant species including large-billed gerygone (*Greygone magnirostris*), red-headed honeyeater (*Myzomela erythrocephala*), Australasian figbird (*Sphecotheres vieilloti*), shining flycatcher (*Myiagra alecto*), yellow white-eye (*Zosterops luteus*), white-bellied sea-eagle (*Haliaeetus leucogaster*, ngirrikati/jankinanki/juburu), helmeted friarbird (*Philemon buceroides*), grey whistler (*Pachycephala simplex*), varied triller (*Lalage leucomela*), brown honeyeater (*Lichmera indistincta*), and rufus-banded honeyeater (*Conopophila albogularis*) (Fensham and Woinarski, 1992). At least three threatened animals are present in the Tiwi Islands dry rainforest: Melville squat-keeled snail (vulnerable$_{NT,}$ *Trochomorpha melvillensis*) (Department of Environment, Parks and Water Security, 2021k), Tiwi Islands treesnail (vulnerable$_{NT,}$ *Amphidromus cognatus*) (Department of Environment, Parks and Water Security, 2021q) and the atlas moth (vulnerable$_{NT}$, *Attacus wardi*)(Department of Environment, Parks and Water Security, 2021a).

Potential threats

Dry rainforests are one of the ecosystems most vulnerable to changes in Australia (Laurance *et al.*, 2011) and globally (Miles *et al.*, 2006). Invasive species, particularly weeds, are an important threat to rainforests around Australia (Metcalfe and Green, 2017). Other regions in Australia have been invaded by lantana (*Lantana camara*) and rubber vine (*Cryptostegia grandiflora*), which reduces recruitment and increase fire severity in a positive feedback cycle (Laurance *et al.*, 2011; Metcalfe and Green, 2017). Water buffalo (*Bubalus bubalis*) and wild pigs (*Sus scrofa*) cause physical destruction through trampling and rubbing, which hinders regeneration (Fensham and Cowie, 1998) (Banfai and Bowman, 2006). There is also an interaction of threats, as invasive ungulates transport weeds and disturb the ecosystem, which leave it more vulnerable to invasion by weeds (Metcalfe and Green, 2017). Weeds also interact with fire. The is a positive feedback between weed invasive and increased fire susceptibility which rapidly degrades dry rainforests (Laurance *et al.*, 2011). Intense wildfires also pose a risk as they may penetrate the otherwise fire-protected ecosystem and high fire frequency may erode the rainforest boundaries (Laurance *et al.*, 2011; Department of Environment and Natural Resources, 2018b). The restricted and patchy distribution renders dry rainforests vulnerable to stochastic events (Laurance *et al.*, 2011; Murray *et al.*, 2017). Further fragmentation may inhibit the movement of frugivore birds and mammals, which play important roles in the dry rainforest regeneration through pollination and the transportation of seeds (Metcalfe and Green, 2017; Department of Environment and Natural Resources, 2018b). Climate change is a significant threat to dry rainforests in the Americas (Miles *et al.*, 2006). Rising temperatures, changing rainfall patterns, and increased CO_2 from climate change will likely impact dry rainforests in complex ways (Laurance *et al.*, 2011). The coastal distribution may cause dry rainforests to be more susceptible to sea level rise and severe weather events (Laurance *et al.*, 2011).

Table 12. Cross-reference of the dry rainforest and vine thicket ecosystem to eight classification schemes spanning the global, national, state and local levels.

Tiwi Island ecosystem type	Global Ecosystem Typology ecosystem functional group (level 3)[1]	International Vegetation Classification formation (level 3)[2]	NVIS major vegetation group[3]	NVIS major vegetation sub-group[3]	Northern Territory vegetation map[4]	Northern Territory macrogroups[5]	Generalised vegetation types of the Tiwi Islands[6]	Tiwi Islands map[7]	NT rainforests[8]
Dry rainforest and vine thicket	T1.2 Tropical/subtropical dry forest and thickets	T1.b4 Tropical seasonally dry forest & thicket	1. Rainforests and vine thickets	62. Dry rainforest or vine thicket	1. Mixed species closed-forest (Monsoon vine-thicket).	1. Australasian & East Malesian dry Forest	4a. Dry monsoon vine thickets	Dry rainforest	9. Semi-deciduous rain forests and vine thickets

[1] Keith, D. A., Ferrer-Paris, J. R., Nicholson, E., Bishop, M. J., Polidoro, B. A., Ramirez-Llodra, E., Tozer, M. G., Nel, J. L., Mac Nally, R., Gregr, E. J., Watermeyer, K. E., Essl, F., Faber-Langendoen, D., Franklin, J., Lehmann, C. E. R., Etter, A., Roux, D. J., Stark, J. S., Rowland, J. A., Brummitt, N.A., Fernandez-Arcaya, U.C., Suthers, I.M., Wiser, S.K., Donohue, I., Jackson, L.J., Pennington, R.T., Iliffe, T.M., Gerovasileiou, V., Giller, P., Robson, B.J., Pettorelli, N., Andrade, A., Lindgaard, A., Tahvanainen, T., Terauds, A., Chadwick, M.A., Murray, N.J., Moat, J., Pliscoff, P., Zager, I. and Kingsford, R. T. (2022). A function-based typology for Earth's ecosystems. *Nature*, *610*(7932), Article 7932. https://doi.org/10.1038/s41586-022-05318-4

[2] Faber-Langendoen, D., Keeler-Wolf, T., Meidinger, D., Tart, D., Hoagland, B., Josse, C., Navarro, G., Ponomarenko, S., Saucier, J.-P., Weakley, A., & Comer, P. (2014). EcoVeg: A new approach to vegetation description and classification. *Ecological Monographs*, *84*(4), 533–561. https://doi.org/10.1890/13-2334.1

[3] DCCEW. (2020). *National Vegetation Information System* (Version 6) [Computer software]. Australian Government. https://www.dcceew.gov.au/environment/land/native-vegetation/national-vegetation-information-system/data-products

[4] Wilson, B. A., Brocklehurst, P. S., Clark, M. J., & Dickonson, K. J. M. (1990). *Vegetation survey of the Northern Territory, Australia, 1990.* [Photos]. NT Map Shop.

[5] Hunter, J.T., Lewis, D., Addicott, E., Luxton, S., Cowie, I., Sparrow, B. and Leitch, E. (2022). A plot-based analysis of the vegetation of the Northern Territory, Australia: a first assessment within the International Vegetation Classification framework', *Vegetation Classification and Survey*, 3, pp. 161–174. Available at: https://doi.org/10.3897/VCS.83045.

[6] Brocklehurst, P., & Edmeades, B. (1998). Vegetation communities. In *The history and natural resources of the Tiwi Islands, Northern Territory.* Parks and Wildlife Commission of the Northern Territory.

[7] Woinarski, J. C. Z., Brennan, K., Cowie, I., Kerrigan, R., & Hempel, C. (2003). *Biodiversity conservation on the Tiwi Islands, Northern Territory: Part 1. Environments and plants*.

[8] Russell-Smith, J. (1991) 'Classification, species richness, and environmental relations of monsoon rain forest in northern Australia', *Journal of Vegetation Science*, 2(2), pp. 259–278. Available at: https://doi.org/10.2307/3235959.

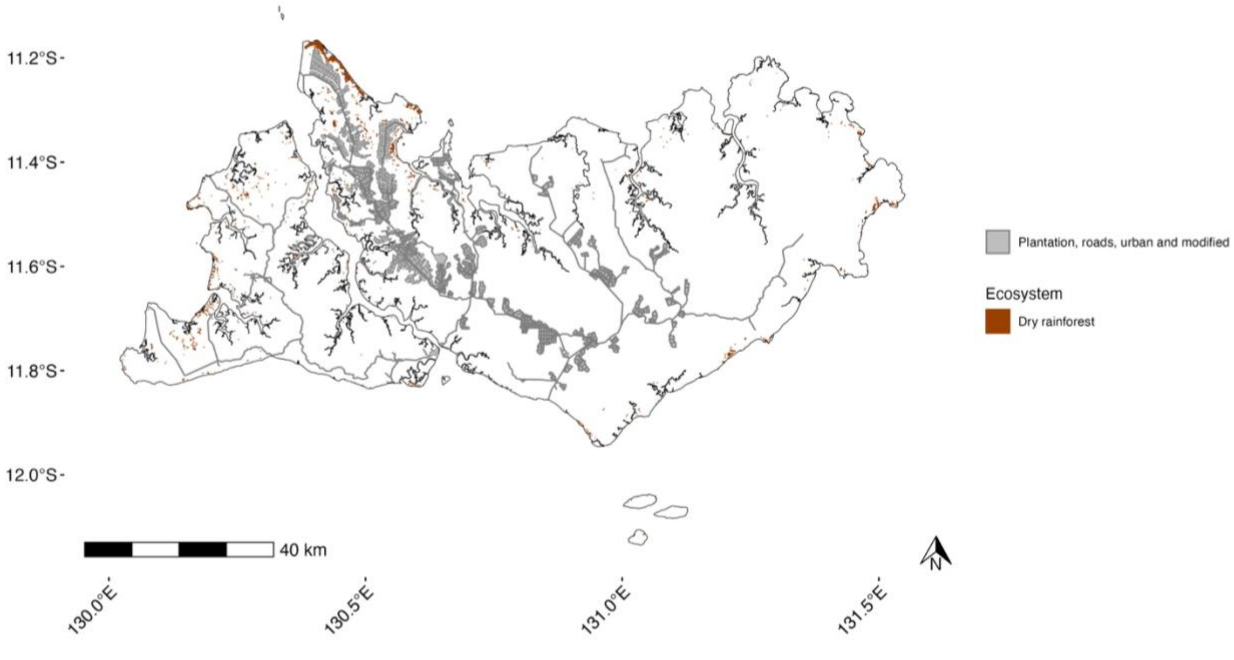


Figure 25. Map of the spatial distribution of the dry rainforest and vine thicket ecosystem on the Tiwi Islands, Australia.

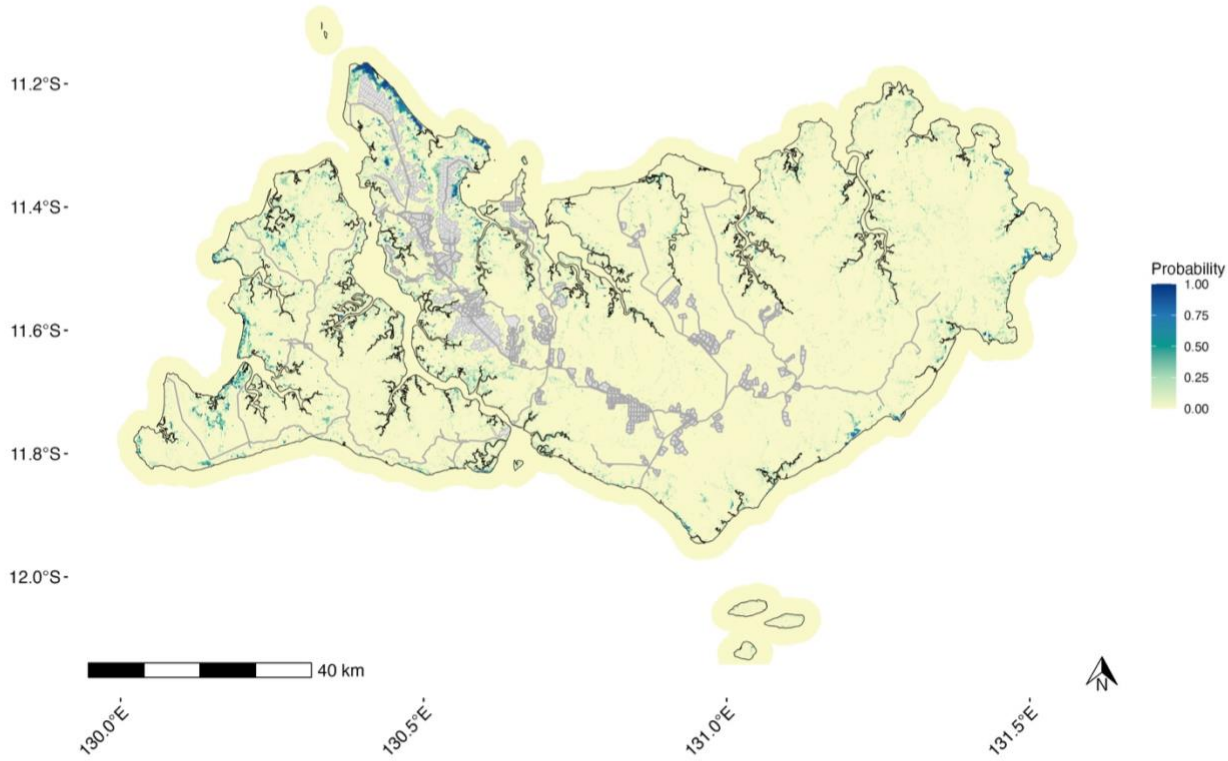


Figure 26. The prediction probability of the dry rainforest and vine thicket ecosystem on the Tiwi Islands, Australia from the random classification model.

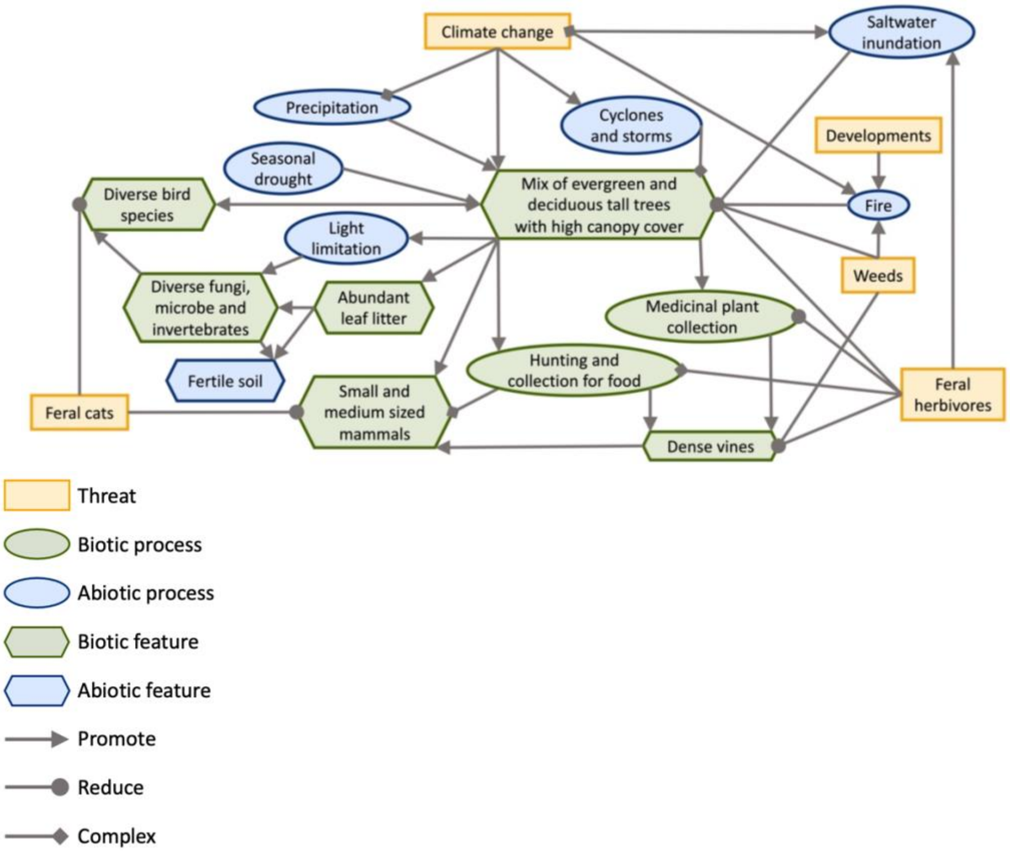


Figure 27. Cause-and-effect conceptual model based on the Red List of Ecosystem conceptual model structure for the dry rainforest and vine thicket ecosystem.

Figure 28. Images of the dry rainforest ecosystem and vine thicket on the Tiwi Islands, Australia.

Melaleuca savanna. Punkaringa.

Ecosystem function

Melaleuca savanna (punkaringa or pikaringini in Tiwi language) is an ecosystem driven by water availability and fire (Good, Smith and Pettit, 2017; Keith *et al.*, 2020). The ecosystem tolerates extreme variation in the soil moisture, occupying a niche with both seasonal waterlogging and drought (Fensham and Kirkpatrick, 1992; Franklin *et al.*, 2007; Good, Smith and Pettit, 2017). Ajimanguwu in Tiwi refers to the free-standing water on the ground when there is poor drainage. Seasonal waterlogging inhibits the growth of savanna species, while seasonal drought and fire inhibit rainforest species (Fensham and Kirkpatrick, 1992; Woinarski, 2004c). The soils are alluvial sands to poorly drained clay plains in drainage depressions, coastal swales, low-lying areas and adjacent to floodplains, again resulting in high soil moisture and seasonal waterlogging (Fensham and Kirkpatrick, 1992; Fensham, 1993; Brocklehurst and Edmeades, 1998; Woinarski *et al.*, 2000). On the Tiwi Islands, there are small areas *Melaleuca* species in riparian areas and swamplands with permanent water (Woinarski *et al.*, 2000; Woinarski, Brennan, Cowie, *et al.*, 2003). During the dry season, fire impacts *Melaleuca* savanna; *Melaleuca* species exhibit fire-resistant traits and recruitment related to fire disturbance (Franklin *et al.*, 2007; Good, Smith and Pettit, 2017).

Geographic extent

On the Tiwi Islands, *Melaleuca* savanna is the ecosystem type with the smallest extent and is distributed throughout the Tiwi Islands (Woinarski *et al.*, 2000; Brocklehurst and Lynch, 2001; Woinarski, Brennan, Cowie, *et al.*, 2003). Similar ecosystems occur across the

Northern Territory (Wilson *et al.*, 1990; Brocklehurst and Lynch, 2001; Franklin *et al.*, 2007) and northern Australia (Good, Smith and Pettit, 2017; DCCEEW, 2020; Keith *et al.*, 2022). Large floodplains with *Melaleuca* forests are absent on the Tiwi Islands as in other regions of the Northern Territory (Brocklehurst and Edmeades, 1998).

Flora

Melaleuca savanna tend to be structurally simple with little shrub layer over a sedge or grass groundcover depending on the water availability (Fensham and Kirkpatrick, 1992; Fensham, 1993; Woinarski *et al.*, 2000). The structure of the vegetation within the ecosystem is variable, from tall (15-30 m) or low forests (as per Specht, 1970) to low woodlands (Fensham and Kirkpatrick, 1992; Fensham, 1993; Woinarski *et al.*, 2000; Woinarski, Brennan, Cowie, *et al.*, 2003). In the Northern Territory, *Melaleuca* floodplain vegetation types tend to have only one or two species in the canopy (Franklin *et al.*, 2007). On the Tiwi Islands, the typical canopy species are *Melaleuca leucadendra, M. viridiflora,* and *M. nervosa* (Fensham, 1993; Woinarski *et al.*, 2000). *Melaleuca viridiflora* occupies a wide niche of environmental conditions (Franklin *et al.*, 2007) and forms low woodlands in drier areas of the Tiwi Islands, similar to the treeless plains ecosystem (Wilson and Fensham, 1994). There are smaller numbers of *M. argentea*, *M. cajuputi*, and *M. dealbata* (Woinarski *et al.*, 2000). In other regions of the Northern Territory, *M. leucadendra* and *M. argentea* tend to occupy riparian areas, alongside the presence of rainforest species, whereas *M. viridiflora* and *M. dealbata* appear to occupy drier areas (Franklin *et al.*, 2007). The understory generally consists of grasses and sedges (Good, Smith and Pettit, 2017), with species on the Tiwi Islands being *Fimbristylis* spp. and *Eriachne burkittii*, *Dapsilanthus spatheceus*, *Tricostularia undulata* and *Xyris complanata* (Fensham, 1993). The *Melaleuca* savannas also support the threatened species *Dendrobium johannis* (near threatened$_{NT}$, vulnerable$_{AUS}$), *Calochilus caeruleus* (wiry beard orchid, vulnerable$_{NT}$), and *Utricularia subulate* (near threatened$_{NT}$), and another seven data deficient species. The *Melaleuca* savanna encompasses multiple vegetation types defined by the dominant species, water salinity, water depth and species richness (Wilson, Brocklehurst and Whitehead, 1990) which have been previously analysed (Woinarski *et al.*, 2000; Brocklehurst and Lynch, 2001). However, the gradual transition between the vegetation types and unclear relationships between dominant species composition can hinder the distinction of vegetation types (Wilson, Brocklehurst and Whitehead, 1990; Franklin *et al.*, 2007).

Fauna

Melaleuca savannas support the lowest ant species richness for fauna compared to the other ecosystems on the Tiwi Islands (Andersen, Woinarski and Hoffmann, 2004). There is a low number of threatened species and a high number of data-deficient animals in the *Melaleuca* savanna compared to other ecosystems on the Tiwi Islands (Woinarski, Brennan, Hempel, *et al.*, 2003). The butler's dunnart (vulnerable$_{AUS, NT}$, *Sminthopsis butleri*, Wurruwataka), Tiwi masked owl (endangered$_{AUS, NT}$, *Tyto novaehollandiae melvillensis*) and the hooded robin (*Melanodryas cucullata)* are known to inhabit or nest in *Melaleuca*-dominated savannas in the Tiwi Islands or the Northern Territory, although the Tiwi Island subspecies of hooded robin (*Melanodryas cucullata melvillensis*) is presumed extinct (Woinarski, Brennan, Hempel, *et al.*, 2003; Woinarski, 2004a; Department of Environment, Parks and Water Security, 2021g, 2021c, 2021j). During flowering, the *Melaleuca* trees likely provide abundant nectar for invertebrates, birds, and mammals, while the grassy understory likely provides seeds, shelter and nesting material, similar to the eucalypt and mixed species savannas.

Potential threats

Due to the importance of groundwater, *Melaleuca* savannas and *Melaleuca* species may be vulnerable to hydrological changes such as surface drainage, rainfall patterns with climate change, and water quality or pollution (Woinarski, Brennan, Cowie, *et al.*, 2003; Good, Smith and Pettit, 2017). Changes to water salinity have caused extensive *Melaleuca* dieback across northern Australia, with suggestions that invasive buffalo also facilitate saltwater intrusion and that the process may be further exacerbated by climate change (Wilson, Brocklehurst and Whitehead, 1990; Finlayson *et al.*, 1999; Bradshaw *et al.*, 2007; Bowman, Prior and De Little, 2010). In other regions of Australia, river regulation and the development of floodplains for urban areas and agriculture have damaged ecosystems that rely on water inundation (Good, Smith and Pettit, 2017). Fire is another crucial ecological function of *Melaleuca* savanna, and changes to the natural fire regimes may reduce the ecological integrity and function (Good, Smith and Pettit, 2017). High severity and late dry season fires would impact tree and grass dynamics and alter *Melaleuca* recruitment (Woinarski, Brennan, Cowie, *et al.*, 2003; Franklin *et al.*, 2007). Weeds have fundamentally altered floodplain ecosystems in other regions of Australia by excluding native grass and sedge communities (Good, Smith and Pettit, 2017). For the Northern Territory, important weeds for wetland communities are mimosa (*Mimosa pigra*), para grass (*Urochloa mutica*) and olive hymenachne (*Hymenachne amplexicaulis*) and may interact with the natural fire regimes required by *Melaleuca* species (Wilson, Brocklehurst and Whitehead, 1990). There is also an interaction between weed spread and invasive ungulates (Good, Smith and Pettit, 2017). Invasive pigs (*Sus scrofa*) and buffalo (*Bubalus bubalis*) consume grassy biomass, root for tubers, trample individual plants, compact soil, spread weeds and disturbs the natural ecosystem, which increases susceptibility to weed invasion (Braithwaite *et al.*, 1984; Fensham and Cowie, 1998; Finlayson *et al.*, 1999; Woinarski, Brennan, Cowie, *et al.*, 2003).

Table 13. Cross-reference of the *Melaleuca* savanna ecosystem to eight classification schemes spanning the global, national, state, and regional scales.

Tiwi Island ecosystem types	Global Ecosystem Typology ecosystem functional group (level 3)[1]	International Vegetation Classification formations (level 3)[2]	NVIS major vegetation group[3]	NVIS major vegetation sub-group[3]	Northern Territory vegetation map[4]	Northern Territory macrogroups[5]	Generalised vegetation types of the Tiwi Islands[6]	Tiwi Islands map[7]
Melaleuca savanna	T4.2 Pyric tussock savanna	T3.a1 Tropical savanna	9. *Melaleuca* forest and woodland	15. *Melaleuca* open forest and woodland	51. *Melaleuca viridiflora* (Broad leaved paperbark), *Eucalyptus* low open-woodland with *Chrysopogon fallax* (Goldern beard grass) grassland understorey.	3. Australian Paperbark *Melaleuca viridiflora*–Long-fruited Bloodwood *Corymbia polycarpa* Forest and Woodland - (e.g. species *Melaleuca viridiflora*, *Grevillea pteridifolia*, *Corymbia polycarpa*, *Lophostemon lactifluus*, *Melaleuca nervosa*)	2b1: *Melaleuca viridiflora* woodland/low woodland with *Eriachne burkitti* open-grassland understorey 2b2: *Melaleuca viridiflora* and *M. nervosa* low open-woodland with tussock grassland understorey	Melaleuca woodland

[1] Keith, D. A., Ferrer-Paris, J. R., Nicholson, E., Bishop, M. J., Polidoro, B. A., Ramirez-Llodra, E., Tozer, M. G., Nel, J. L., Mac Nally, R., Gregr, E. J., Watermeyer, K. E., Essl, F., Faber-Langendoen, D., Franklin, J., Lehmann, C. E. R., Etter, A., Roux, D. J., Stark, J. S., Rowland, J. A., Brummitt, N.A., Fernandez-Arcaya, U.C., Suthers, I.M., Wiser, S.K., Donohue, I., Jackson, L.J., Pennington, R.T., Iliffe, T.M., Gerovasileiou, V., Giller, P., Robson, B.J., Pettorelli, N., Andrade, A., Lindgaard, A., Tahvanainen, T., Terauds, A., Chadwick, M.A., Murray, N.J., Moat, J., Pliscoff, P., Zager, I. and Kingsford, R. T. (2022). A function-based typology for Earth's ecosystems. *Nature*, *610*(7932), Article 7932. https://doi.org/10.1038/s41586-022-05318-4

[2] Faber-Langendoen, D., Keeler-Wolf, T., Meidinger, D., Tart, D., Hoagland, B., Josse, C., Navarro, G., Ponomarenko, S., Saucier, J.-P., Weakley, A., & Comer, P. (2014). EcoVeg: A new approach to vegetation description and classification. *Ecological Monographs*, *84*(4), 533–561. https://doi.org/10.1890/13-2334.1

[3] DCCEW. (2020). *National Vegetation Information System* (Version 6) [Computer software]. Australian Government. https://www.dcceew.gov.au/environment/land/native-vegetation/national-vegetation-information-system/data-products

[4] Wilson, B. A., Brocklehurst, P. S., Clark, M. J., & Dickonson, K. J. M. (1990). *Vegetation survey ofthe Northern Territory, Australia, 1990.* [Photos]. NT Map Shop.

[5] Hunter, J.T., Lewis, D., Addicott, E., Luxton, S., Cowie, I., Sparrow, B. and Leitch, E. (2022). A plot-based analysis of the vegetation of the Northern Territory, Australia: a first assessment within the International Vegetation Classification framework', *Vegetation Classification and Survey*, 3, pp. 161–174. Available at: https://doi.org/10.3897/VCS.83045.

[6] Brocklehurst, P., & Edmeades, B. (1998). Vegetation communities. In *The history and natural resources of the Tiwi Islands, Northern Territory.* Parks and Wildlife Commission of the Northern Territory.

[7] Woinarski, J. C. Z., Brennan, K., Cowie, I., Kerrigan, R., & Hempel, C. (2003). *Biodiversity conservation on the Tiwi Islands, Northern Territory: Part 1. Environments and plants*.

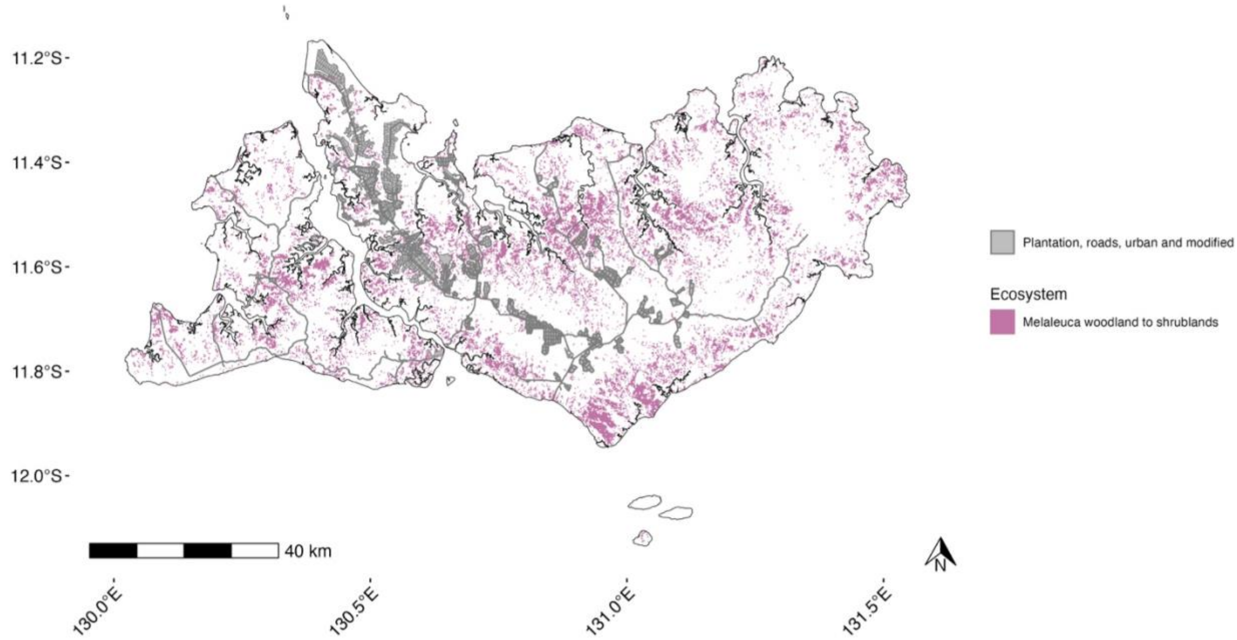


Figure 29. Map of the spatial distribution of the *Melaleuca* savanna ecosystem on the Tiwi Islands, Australia.

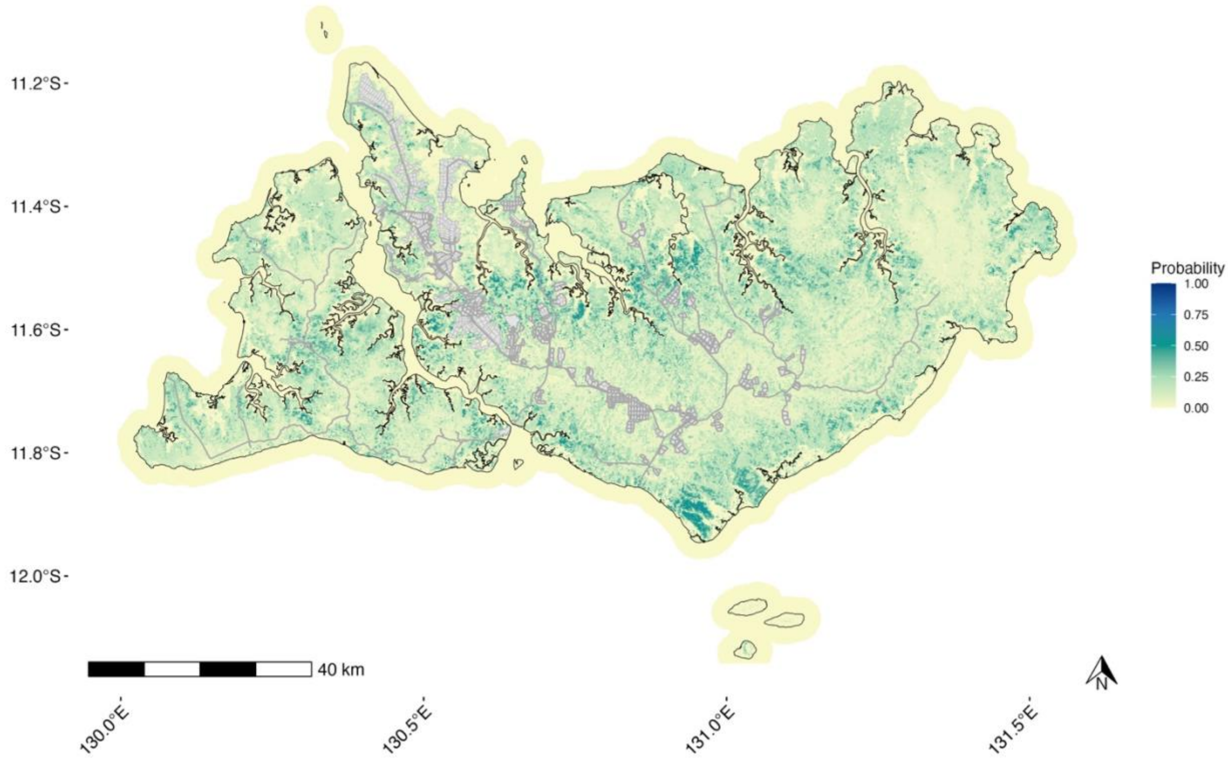


Figure 30. The predicted probability of the *Melaleuca* savanna ecosystem for the Tiwi Islands from the random forest classification model.

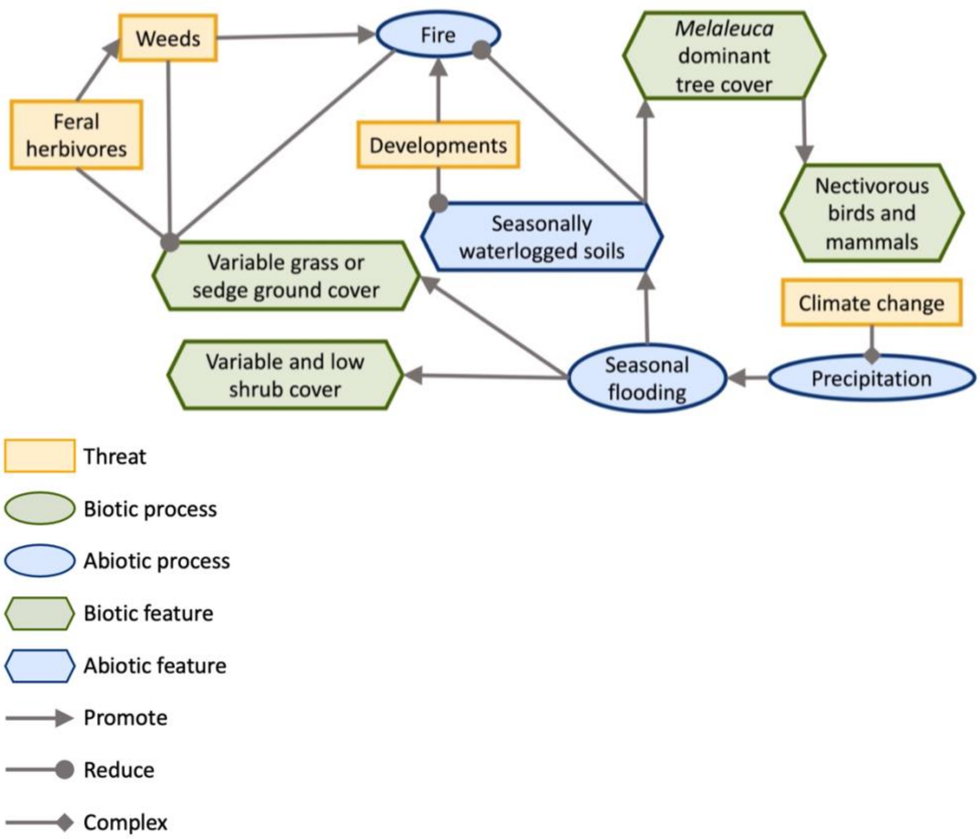


Figure 31. Cause-and-effect conceptual model based on the Red List of Ecosystem conceptual model structure for the *Melaleuca* savanna ecosystem.






Figure 32. Images of the *Melaleuca* savanna ecosystem on the Tiwi Islands, Australia.

Grassland and sedgeland wetlands. Turringiya.

Ecosystem function

Grasslands and sedgeland wetlands (turringiya in Tiwi Language) are seasonally inundated wetlands on drainage depressions and floodplains in the upper reaches of creeks and rivers (Woinarski *et al.*, 2000). These wetlands are low-lying, often coastal, and on poorly drained soils (Hollingsworth *et al.*, 2006). The seasonal water input and poor draining soils result in seasonal waterlogging and standing water (ajimanguwu in Tiwi) (Woinarski and Baker, 2002). Seasonal soil moisture is the key driving process that creates the ecosystem structure and traits (Catford *et al.*, 2017; Keith *et al.*, 2020).

Geographic extent

Floodplain wetlands are widespread across northern Australia and an iconic ecosystem in the Alligator Rivers Region in Kakadu National Park, Northern Territory (Wilson *et al.*, 1990; Catford *et al.*, 2017). Given the size of the Tiwi Islands, wetlands are relatively small compared to the mainland (Wilson *et al.*, 1990). On the Tiwi Islands, floodplain wetlands are extensive at Andranagoo Creek, Melville Island (Woinarski and Baker, 2002).

Flora

Species composition varies between dry and wet seasons. Tussock grasses dominate during drier periods of the year; sedges and rushes replace the grasses with extensive rainfall and free-standing water during the wet season (Brocklehurst and Edmeades, 1998; Fox *et al.*, 2001). During the wet season, sedge cover can reach 100%, with common species being *Eleocharis dulcis* (water chestnut, kirlinja) and *Schoenoplectus litoralis* (Brocklehurst and Edmeades, 1998; Woinarski *et al.*, 2000). Areas with constant soil moisture, such as spring-fed creeks, may retain sedges as the dominant ground cover (Brocklehurst and Edmeades, 1998). Common species are the grass *Sporobolus virginicus* (marine couch) in coastal or drier periods and *Nymphaea violacea* (water lily, purnarrika, malaritinga) in open water providing edible tubers (Brocklehurst and Edmeades, 1998; Woinarski *et al.*, 2000; Woinarski, Brennan, Cowie, *et al.*, 2003). These species are common in other floodplains of tropical Australia (Catford *et al.*, 2017). The grasslands and sedgelands may also support five data-deficient species (Woinarski, Brennan, Cowie, *et al.*, 2003). On the fringes of the wetlands, isolated individuals or scattered clumps of shrubs or trees may appear, usually *Melaleuca viridiflora* (Punkaringa) and *Pandanus spiralis* (Miyaringa) (Brocklehurst and Edmeades, 1998; Woinarski, Brennan, Cowie, *et al.*, 2003).

Fauna

The extensive food resources from *E. dulcis* support transitory populations of magpie geese (*Anseranas semipalmata*, mayimampi/awurnanka/narringari/pukumwaka/wurrikiliki). Magpie geese are an important species hunted for food (TLC *et al.*, 2001). The Tiwi masked owl (endangered$_{\text{AUS, NT}}$, *Tyto novaehollandiae melvillensis*) forages in open grassy areas (Woinarski, Brennan, Hempel, *et al.*, 2003; Department of Environment, Parks and Water Security, 2021j). In other regions of the Northern Territory, similar floodplain wetlands support extensive avian communities (Finlayson *et al.*, 2006). Mammals may also access resources from wetlands, such as water during drier periods (Finlayson *et al.*, 2006). On the Tiwi Islands, the floodplains are expected to provide habitat for the data deficient and threatened water mouse (*Xeromys myoides*, vulnerable$_{\text{AUS}}$) (Woinarski, Brennan, Hempel, *et al.*, 2003). In the Kakadu National Park, the extensive floodplains also support many species of reptiles, amphibians, fish and invertebrates (Finlayson *et al.*, 2006).

Potential threats

Tropical wetlands in northern Australia are in critical danger of weed invasion (Finlayson *et al.*, 1999; Catford *et al.*, 2017). Exotic perennial pasture grasses threaten tussock grassland and sedgeland ecosystems by outcompeting native species, changing food sources for fauna, and potentially altering fire regimes (Fensham and Cowie, 1998). For the Tiwi Islands, weeds which may pose risks to the tussock grassland and sedgeland wetlands include mimosa (*Mimosa pigra*), para grass (*Urochloa mutica*) and olive hymenachne (*Hymenachne amplexicaulis*) (Wilson, Brocklehurst and Whitehead, 1990; Woinarski and Baker, 2002;

Woinarski, Brennan, Cowie, *et al.*, 2003) which are common weed species in other regions of northern Australia (Finlayson *et al.*, 1999). Weeds can both cause and indicate ecosystem degradation for wetlands in Australia (Catford *et al.*, 2017). Feral and invasive animals also pose a substantial risk to the grassland and sedgeland ecosystems in Australia (Catford *et al.*, 2017). Feral buffalo (*Bubalus bubalis*) and pigs (*Sus scrofa*) alter soil salinity, wetland hydrology, and have direct impacts through grazing, rooting, trampling, and wallowing (Fensham and Cowie, 1998; Finlayson *et al.*, 1999; Woinarski and Baker, 2002). There also appears to be an interaction between invasive animals and weeds, through both disturbing natural ecosystems, spreading weeds and consuming weedy biomass (Finlayson *et al.*, 1999), and between invasive animals and saltwater intrusion (Finlayson *et al.*, 1999). Given the importance of soil moisture fluxes for the ecosystem, changes to the hydrology through water extraction, flow regulation and climate change through precipitation and sea level rise may be particularly harmful to the integrity of the ecosystem (Woinarski and Baker, 2002; Catford *et al.*, 2017). Increased saline water intrusion may turn freshwater floodplains into saline wetlands or salt flats (Wilson, Brocklehurst and Whitehead, 1990; Finlayson *et al.*, 1999, 2006; Catford *et al.*, 2017). Cane toads may threaten amphibian fauna of freshwater wetlands and predators (Finlayson *et al.*, 1999, 2006), although cane toads are not currently established on the Tiwi Islands due to effective biosecurity.

Table 14. Cross-reference of the tussock grassland and sedgeland wetland ecosystem to eight classification schemes spanning the global, national, state, and regional scale.

Tiwi Islands ecosystem type	Global Ecosystem Typology ecosystem functional group (level 3)[1]	International Vegetation Classification system formation (level 3)[2]	NVIS major vegetation group[3]	NVIS major vegetation sub-group[3]	Northern Territory vegetation map[4]	Northern Territory macrogroups[5]	Generalised vegetation types of the Tiwi Islands[6]	Tiwi Island vegetation map [7]
Grassland and sedgeland wetlands	TF1.4 Seasonal floodplain marshes	TF1.b3 Marsh, wet meadow & shrub wetland	21. Other grasslands, herblands, sedgelands and rushlands	38. Wet tussock grassland with herbs, sedges or rushes, herblands or ferns 63. Sedgelands, rushes or reeds	54. Mixed closed-grassland/sedgeland (Seasonal Floodplain)	14. Northern Australia Tropical Swamp Grass *Pseudoraphis spinescens*–Water Chestnut *Eleocharis dulcis*–Water Lily *Nymphaea violacea* Grassland and Sedgeland	6. Swamps / sedgeland	Swamp / sedgeland

[1] Keith, D. A., Ferrer-Paris, J. R., Nicholson, E., Bishop, M. J., Polidoro, B. A., Ramirez-Llodra, E., Tozer, M. G., Nel, J. L., Mac Nally, R., Gregr, E. J., Watermeyer, K. E., Essl, F., Faber-Langendoen, D., Franklin, J., Lehmann, C. E. R., Etter, A., Roux, D. J., Stark, J. S., Rowland, J. A., Brummitt, N.A., Fernandez-Arcaya, U.C., Suthers, I.M., Wiser, S.K., Donohue, I., Jackson, L.J., Pennington, R.T., Iliffe, T.M., Gerovasileiou, V., Giller, P., Robson, B.J., Pettorelli, N., Andrade, A., Lindgaard, A., Tahvanainen, T., Terauds, A., Chadwick, M.A., Murray, N.J., Moat, J., Pliscoff, P., Zager, I. and Kingsford, R. T. (2022). A function-based typology for Earth's ecosystems. *Nature*, *610*(7932), Article 7932. https://doi.org/10.1038/s41586-022-05318-4

[2] Faber-Langendoen, D., Keeler-Wolf, T., Meidinger, D., Tart, D., Hoagland, B., Josse, C., Navarro, G., Ponomarenko, S., Saucier, J.-P., Weakley, A., & Comer, P. (2014). EcoVeg: A new approach to vegetation description and classification. *Ecological Monographs*, *84*(4), 533–561. https://doi.org/10.1890/13-2334.1

[3] DCCEW. (2020). *National Vegetation Information System* (Version 6) [Computer software]. Australian Government. https://www.dcceew.gov.au/environment/land/native-vegetation/national-vegetation-information-system/data-products

[4] Wilson, B. A., Brocklehurst, P. S., Clark, M. J., & Dickonson, K. J. M. (1990). *Vegetation survey of the Northern Territory, Australia, 1990.* [Photos]. NT Map Shop.

[5] Hunter, J.T., Lewis, D., Addicott, E., Luxton, S., Cowie, I., Sparrow, B. and Leitch, E. (2022). A plot-based analysis of the vegetation of the Northern Territory, Australia: a first assessment within the International Vegetation Classification framework', *Vegetation Classification and Survey*, 3, pp. 161–174. Available at: https://doi.org/10.3897/VCS.83045.

[6] Brocklehurst, P., & Edmeades, B. (1998). Vegetation communities. In *The history and natural resources of the Tiwi Islands, Northern Territory.* Parks and Wildlife Commission of the Northern Territory.

[7] Woinarski, J. C. Z., Brennan, K., Cowie, I., Kerrigan, R., & Hempel, C. (2003). *Biodiversity conservation on the Tiwi Islands, Northern Territory: Part 1. Environments and plants* (1).

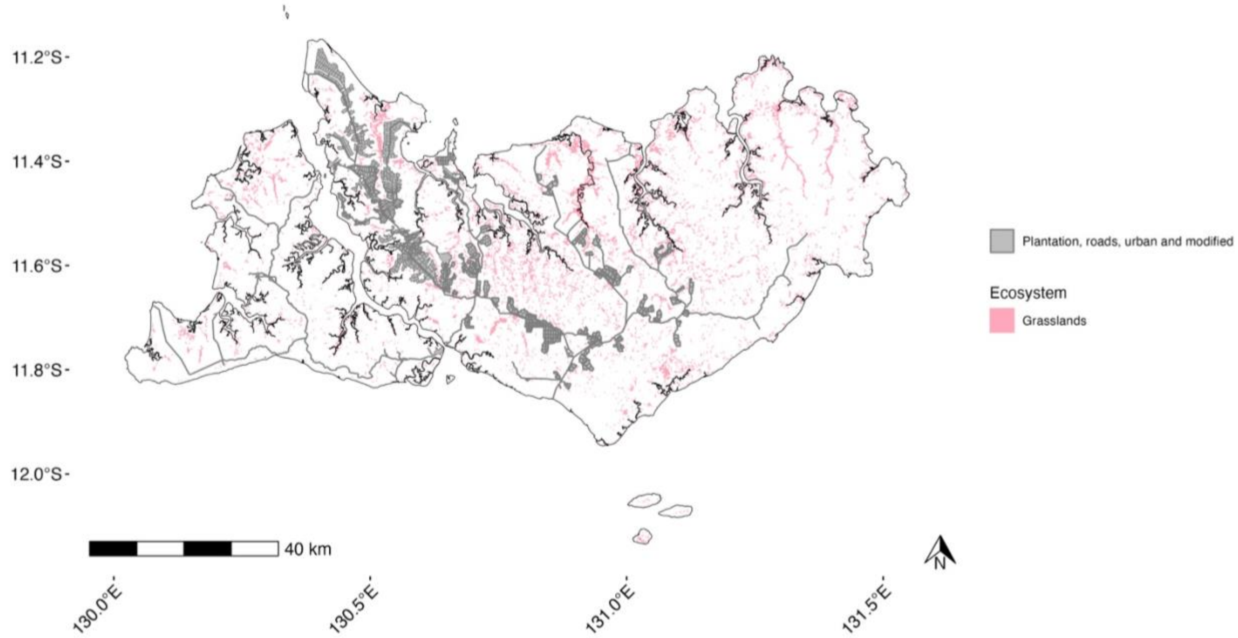


Figure 33. Map of the spatial distribution of the tussock grassland and sedgeland wetland ecosystem on the Tiwi Islands, Australia.

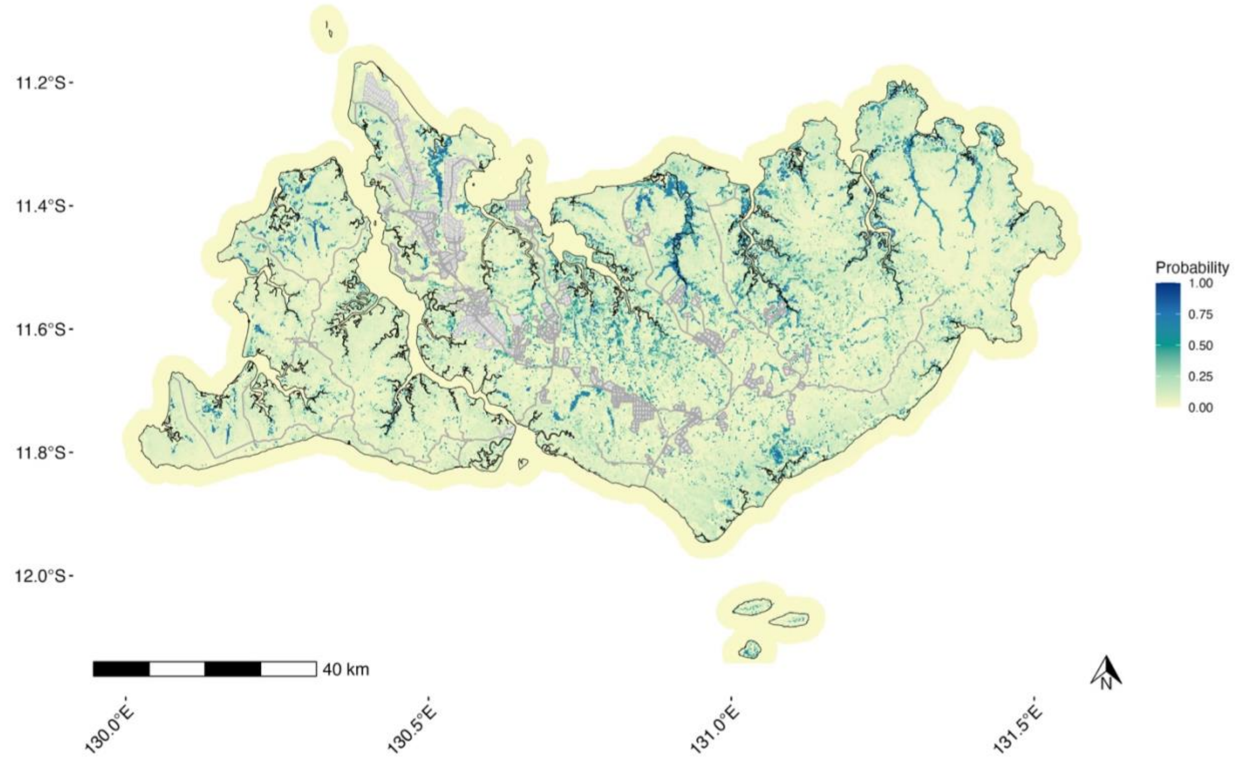


Figure 34. The prediction probability of the tussock grassland and sedgeland wetland ecosystem on the Tiwi Islands, Australia from the random classification model.

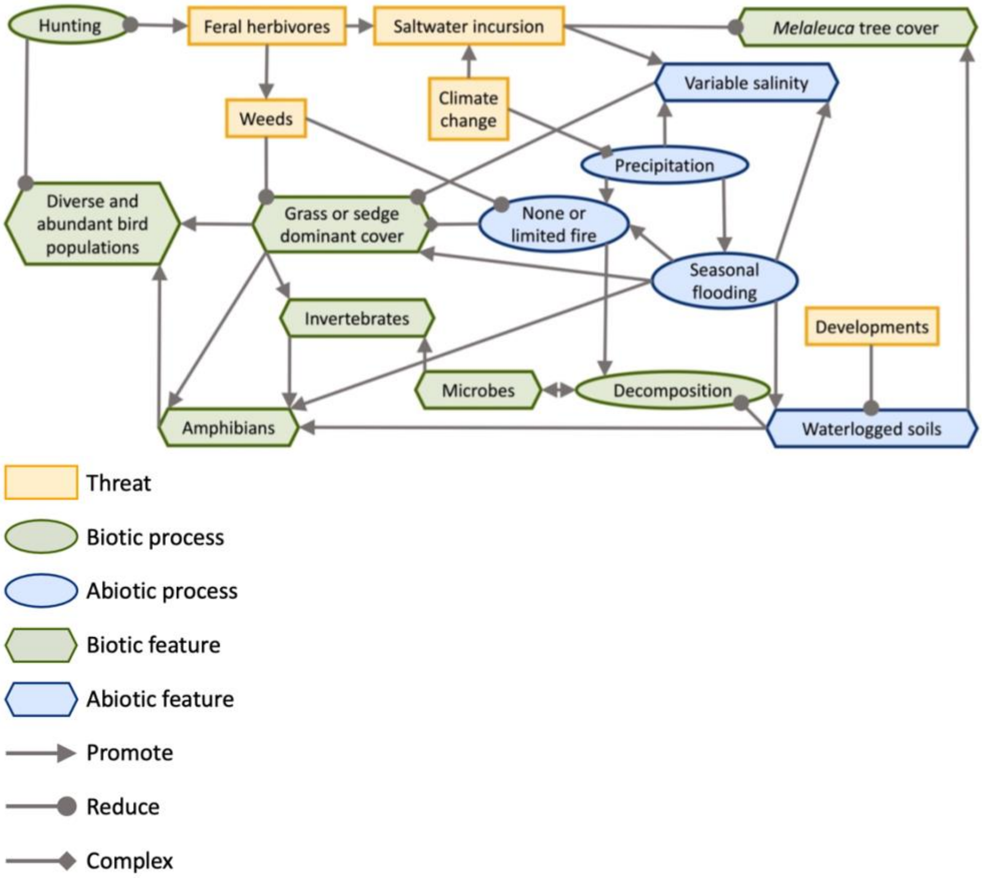


Figure 35. Cause-and-effect conceptual model based on the Red List of Ecosystem conceptual model structure for the tussock grassland and sedgeland wetland ecosystem.

Figure 36. Images of the tussock grassland and sedgeland wetland ecosystems on the Tiwi Islands, Australia.

Mangrove. Mirriparinga and pamparinga.

Ecosystem function

Mangroves (mirriparinga or pamparinga in Tiwi language) are intertidal communities that occupy the coastal fringes between the terrestrial, marine and often freshwater realms (Brocklehurst and Edmeades, 1998; Woinarski, Brennan, Cowie, *et al.*, 2003; Department of Environment and Natural Resources, 2018a; Keith *et al.*, 2020). High and regular tidal inundation is a driving force in community structure, strongly driving the floral species (Woinarski, Brennan, Cowie, *et al.*, 2003; Hollingsworth *et al.*, 2006; Wightman, 2006; Keith *et al.*, 2020) and creating strong zonation in the biotic communities (Rogers *et al.*, 2017). The saline, alluvial soils are deep, non-gravely, and very poorly drained (Hollingsworth *et al.*, 2006). The high salinity drives plant traits (Rogers *et al.*, 2017). The ecosystem is also named 'mangal' (e.g. Woinarski *et al.*, 2000, 2003) to differentiate between the mangrove plants from the Rhizophoraceae family and the ecosystem (Rogers *et al.*, 2017).

Geographical extent

Mangroves are found globally (Thomas *et al.*, 2017; Bunting *et al.*, 2018; Giri, 2021), around Australia (Rogers *et al.*, 2017) and extensively in the Northern Territory (Wilson *et al.*, 1990; Finlayson, 1999; Wightman, 2006; Department of Environment and Natural Resources, 2018a). On the Tiwi Islands, mangroves dominate the highly convoluted coastline at the saltwater margins and creeks and occur across the islands (Messel, Wells and Green, 1979; Wilson *et al.*, 1990; Woinarski *et al.*, 2000).

Flora

Mangroves in the tropical northern regions of Australia tend to be floristically diverse, especially compared to equivalent ecosystems in southern Australia which is true of the Tiwi Islands (Wightman, 2006; Rogers *et al.*, 2017). Mangrove flora varies in structure from low closed forest to open forests and woodlands (Messel, Wells and Green, 1979; Brocklehurst and Edmeades, 1998). The strong floristic zonation is exhibited clearly on the Tiwi Islands as vegetation types (Messel, Wells and Green, 1979; Brocklehurst and Edmeades, 1998), with the typical dominant species being *Sonneratia alba* (Pornupan mangrove, maripwanga), *S. caseolaris* (Red-flowered pornupan mangrove), *Rhizophora stylosa* (Spotted mangrove, pukulijupa), *R. apiculata* (Tall stilt mangrove, pukulijupa/purirringa), *Bruguiera parviflora* (Small-flowered orange mangrove, nurninga), *Diospyros littorea* (Ebony mangrove, yawurlama), *Xylocarpus mekongensis* (Cedar mangrove, pupwurrupwani), *Ceriops australis* (Yellow mangrove, marrakali), and *Lumnitzera racemosa* (white-flowered black mangrove, mijinga). Isolated populations of the *Nypa fruticans* (mangrove Palm, rola) and the threatened species *Thrixspermum congestum* are also uniquely present and rarely found elsewhere in the Northern Territory (Department of Environment, Parks and Water Security, 2021p).

Fauna

Mangroves provide habitat, protection and food resources to various marine, intertidal and terrestrial fauna (Department of Environment and Natural Resources, 2018a). The nearby Darwin harbour and mangrove ecosystems support a highly diverse vertebrate and invertebrate faunal community (Metcalfe, 2007). The complex roots create nursery grounds for fish species, crabs and marine invertebrates (Wightman, 2006; Metcalfe, 2007; Department of Environment and Natural Resources, 2018a). Mangroves on the Tiwi Islands and in the Northern Territory support distinctive bird communities (Noske, 1996; Chatto, 2003; Finlayson *et al.*, 2006) that roost in the trees and feed on the marine and intertidal organisms, creating complex food webs. Crocodiles, monitors, bats and possums may also inhabit mangroves in the Northern Territory (Wightman, 2006). On the Tiwi Islands, mangroves importantly support the threatened water mouse (Water mouse, *Xeromys myoides*), listed as vulnerable nationally and data deficient in the Northern Territory (Woinarski, 2000, 2006; Department of Environment and Natural Resources, 2018a). Molluscs and worms are principal food sources collected by Tiwi people, especially *Telescopium Telescopium* (long bum/mud whelk, piranga), *Terebralia palustris* (mud whelk, tuwarirrukwa), *Polymesoda erosa* (mud mussel, jukwarringa), *Anadara granosa* (cockle, mirnangini), *Bactronophorous thoracites* (mangrove worm, yuwurli), and *Bankia australis* (cheeky mangrove worm, wakatapa) (TLC *et al.*, 2001; Wightman, 2006; Metcalfe, 2007).

Potential threats

Compared to other countries, Australian mangroves are largely intact, with little change to the geographic extent (Thomas et al., 2017). On the Tiwi Islands, mangroves appear to be retreating in some areas of the coastline, which has also been observed by Tiwi People (Barnett et al., 2023). Sea level rise is a crucial threat globally (Gilman et al., 2008) and has resulted in landward migration in other regions (Lovelock *et al.*, 2015; Murray *et al.*, 2019). Sea level variability has also been implicated in mangrove dieback in Australia (Lovelock et al., 2017). Salt water intrusion into the upper reaches of rivers may alter mangrove community structure and zonation (Finlayson et al., 1999). Globally, anthropogenic impacts and clearing harm mangroves (Rogers *et al.*, 2017; Thomas *et al.*, 2017; Giri, 2021). Within

Australia, mangroves in the Northern Territory have not been cleared to the same extent as in other states (Wightman, 2006), with only some localised clearing for developments, for example, near Darwin (Department of Environment and Natural Resources, 2018a). Other anthropogenic effects include fuel spills from shipping and tourism, sedimentation, pollution, nutrient enrichment and changes to hydrology, such as storm water run-off (Finlayson *et al.*, 1999; Department of Environment and Natural Resources, 2018a).

Table 15. Cross-reference of the mangrove ecosystem to eight classification schemes spanning the global, national, state and regional scales.

Tiwi Islands ecosystem type	Global Ecosystem Typology ecosystem functional group (level 3)[1]	International Vegetation Classification formations (level 3)[2]	NVIS major vegetation group[3]	NVIS major vegetation sub-group[3]	Northern Territory vegetation map[4]	Northern Territory macrogroups[5]	Generalised vegetation types of the Tiwi Islands[6]	Tiwi Island vegetation map[7]
Mangroves	MFT1.2 Intertidal forests and shrublands	MFT1.a2 Mangrove	23. Mangrove	23. Mangrove	105. Mangal low closed-forest (mangroves)	(MG2) West Pacific (East Melanesia, Micronesia, Polynesia) Mangrove (M208)	3. Mangrove closed forest	Mangal forest

[1] Keith, D. A., Ferrer-Paris, J. R., Nicholson, E., Bishop, M. J., Polidoro, B. A., Ramirez-Llodra, E., Tozer, M. G., Nel, J. L., Mac Nally, R., Gregr, E. J., Watermeyer, K. E., Essl, F., Faber-Langendoen, D., Franklin, J., Lehmann, C. E. R., Etter, A., Roux, D. J., Stark, J. S., Rowland, J. A., Brummitt, N.A., Fernandez-Arcaya, U.C., Suthers, I.M., Wiser, S.K., Donohue, I., Jackson, L.J., Pennington, R.T., Iliffe, T.M., Gerovasileiou, V., Giller, P., Robson, B.J., Pettorelli, N., Andrade, A., Lindgaard, A., Tahvanainen, T., Terauds, A., Chadwick, M.A., Murray, N.J., Moat, J., Pliscoff, P., Zager, I. and Kingsford, R. T. (2022). A function-based typology for Earth's ecosystems. *Nature*, *610*(7932), Article 7932. https://doi.org/10.1038/s41586-022-05318-4

[2] Faber-Langendoen, D., Keeler-Wolf, T., Meidinger, D., Tart, D., Hoagland, B., Josse, C., Navarro, G., Ponomarenko, S., Saucier, J.-P., Weakley, A., & Comer, P. (2014). EcoVeg: A new approach to vegetation description and classification. *Ecological Monographs*, *84*(4), 533–561. https://doi.org/10.1890/13-2334.1

[3] DCCEW. (2020). *National Vegetation Information System* (Version 6) [Computer software]. Australian Government. https://www.dcceew.gov.au/environment/land/native-vegetation/national-vegetation-information-system/data-products

[4] Wilson, B. A., Brocklehurst, P. S., Clark, M. J., & Dickonson, K. J. M. (1990). *Vegetation survey of the Northern Territory, Australia, 1990.* [Photos]. NT Map Shop.

[5] Hunter, J.T., Lewis, D., Addicott, E., Luxton, S., Cowie, I., Sparrow, B. and Leitch, E. (2022). A plot-based analysis of the vegetation of the Northern Territory, Australia: a first assessment within the International Vegetation Classification framework', *Vegetation Classification and Survey*, 3, pp. 161–174. Available at: https://doi.org/10.3897/VCS.83045.

[6] Brocklehurst, P., & Edmeades, B. (1998). Vegetation communities. In *The history and natural resources of the Tiwi Islands, Northern Territory.* Parks and Wildlife Commission of the Northern Territory.

[7] Woinarski, J. C. Z., Brennan, K., Cowie, I., Kerrigan, R., & Hempel, C. (2003). *Biodiversity conservation on the Tiwi Islands, Northern Territory: Part 1. Environments and plants*.

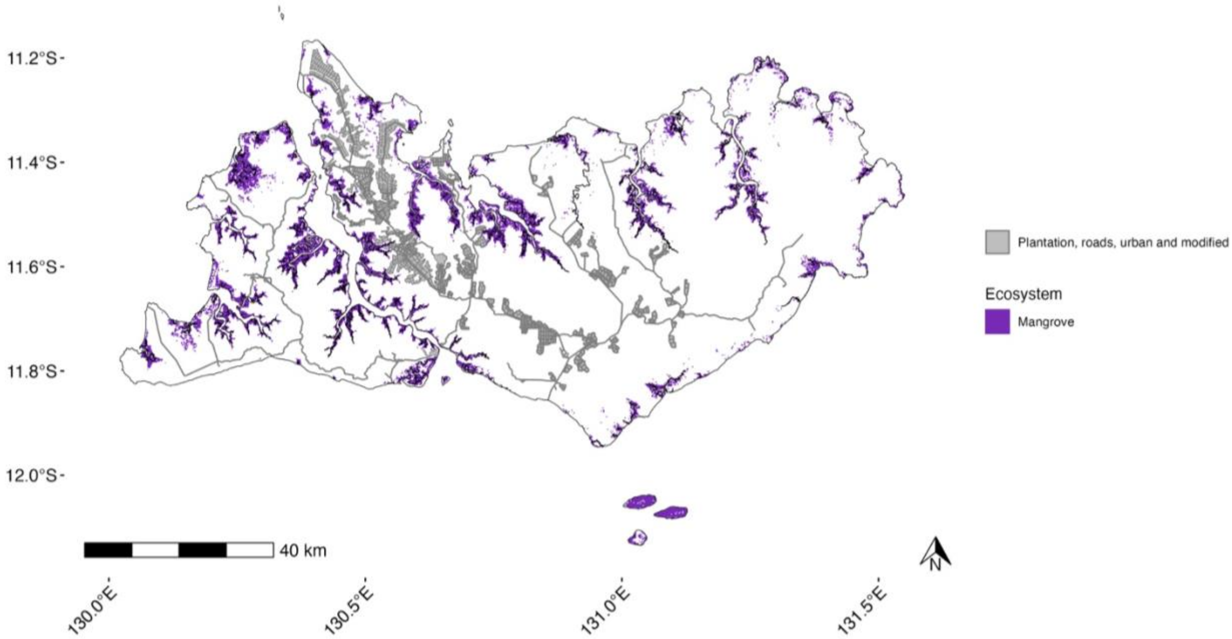


Figure 37. Map of the spatial distribution of the mangrove ecosystem on the Tiwi Islands, Australia.

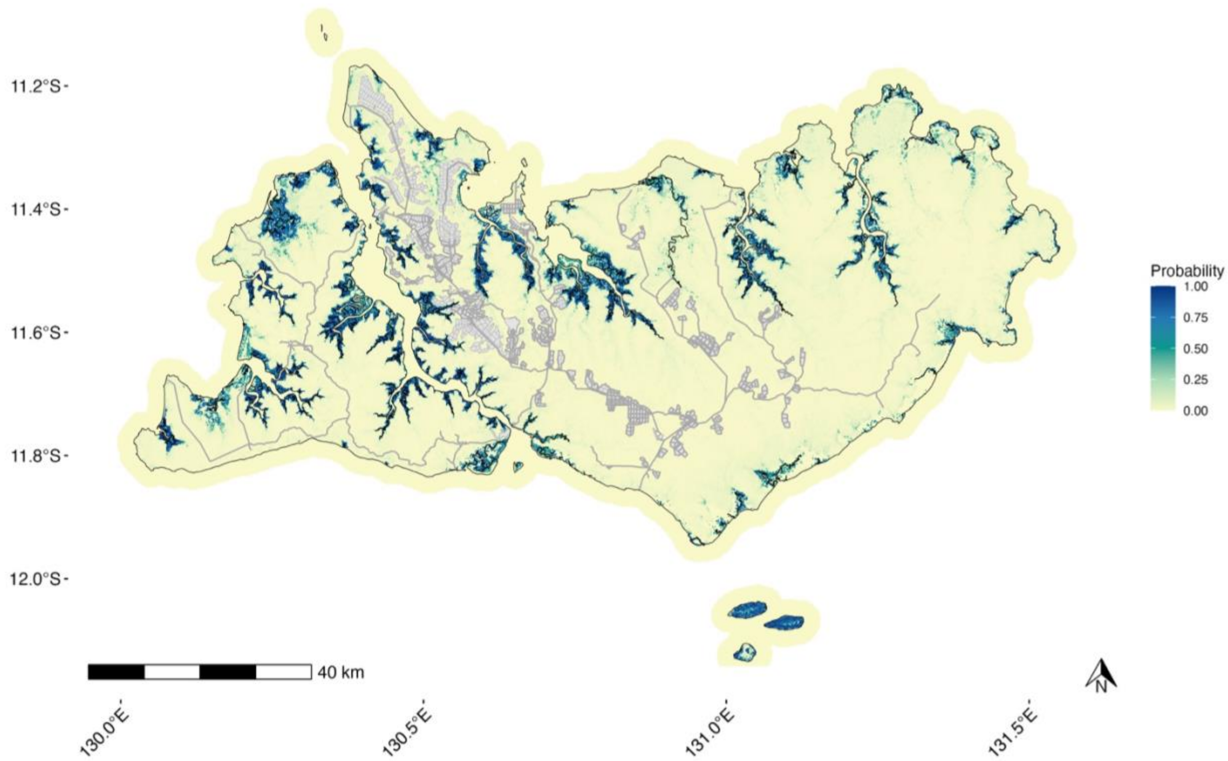


Figure 38. The prediction probability of the mangrove ecosystem on the Tiwi Islands, Australia from the random classification model.

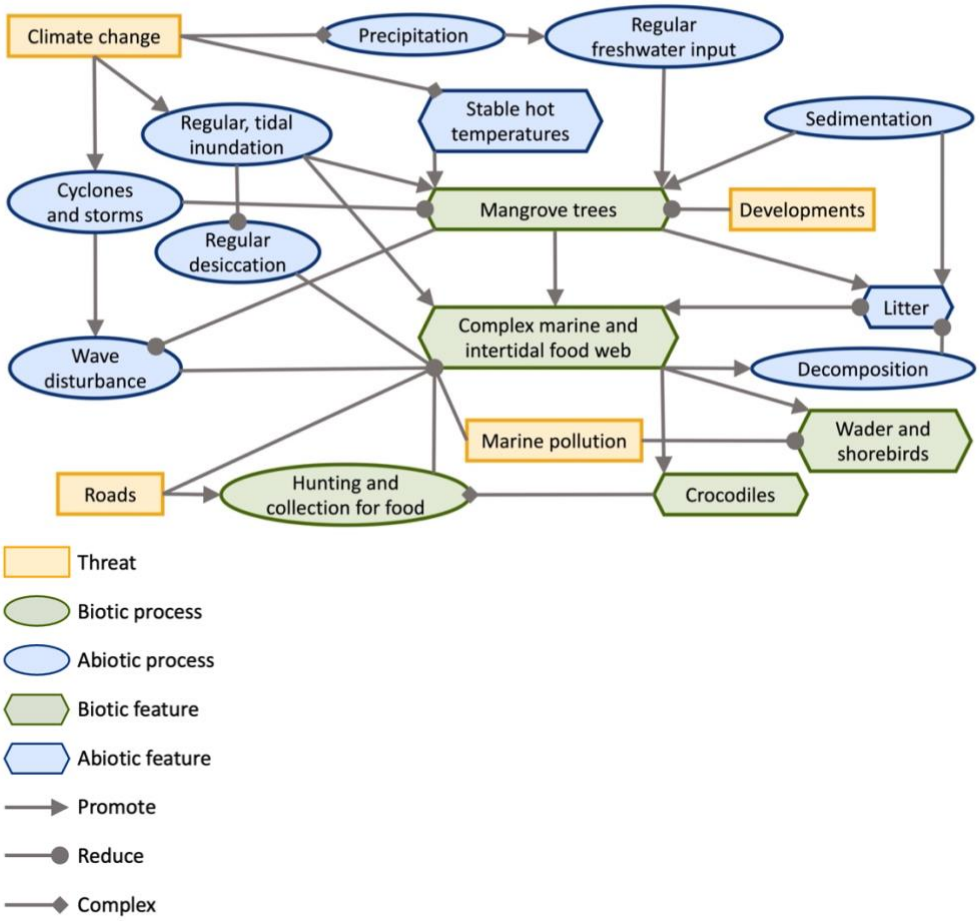


Figure 39. Cause-and-effect conceptual model based on the Red List of Ecosystem conceptual model structure for the mangrove ecosystem.

Figure 40. Images of the mangrove ecosystem on the Tiwi Islands, Australia.

Coastal saltmarsh and mud flats. *Yarti*.

Ecosystem function

Coastal saltmarsh and mud flats (*yarti* in Tiwi language) are an open saline wetland ecosystem which encompass intertidal vegetated saltmarshes and intertidal or supratidal muddy flats (Finlayson, 1999). The ecosystem is a member of the 'MFT1.3 Coastal Saltmarsh and reedbeds' ecosystem functional type (Keith *et al.*, 2022). The saltmarsh lies in low elevations adjacent to the ocean and experiences irregular tidal inundation, low to no wave energy and high desiccation rates, creating a highly saline environment (Creighton, Gillies and McLeod, 2015; Rogers *et al.*, 2017; Keith *et al.*, 2020). The saltmarsh often occurs landward of mangroves with slightly higher elevation, which creates tidal inundation rather than constant inundation as experienced by mangroves (Creighton, Gillies and McLeod, 2015; Rogers *et al.*, 2017). The poorly drained marine mud soils become anoxic at depth (Hollingsworth *et al.*, 2006; Keith *et al.*, 2020). The high salinity and severe desiccation impedes floristic and structural diversity and drives species traits, community structure and zonation patterns (Fox *et al.*, 2001; Creighton, Gillies and McLeod, 2015; Keith *et al.*, 2022).

Geographical extent

Salt flats are prominent throughout the Tiwi-Cobourg bioregion, on the Tiwi Islands and Cobourg Peninsula (Woinarski and Baker, 2002). Extensive areas of salt and mud flats appear on the east of Melville Island in areas of Yimpinari clan lands and commonly intermix with the extensive mangrove ecosystem (Wilson *et al.*, 1990; TLC *et al.*, 2001). Coastal saltmarsh is common in the Northern Territory (Delaney, 2012), and around Australia (Finlayson, 1999; Creighton, Gillies and McLeod, 2015; Rogers *et al.*, 2017; Clark, Fischer and Hunter, 2021). In northern Australia, saltmarsh tends to form extensive areas landward of mangroves (Rogers *et al.*, 2017).

Flora

On the Tiwi Islands, saltmarsh is typically denuded in large areas with scattered chenopods, samphire or *Sporobolus virginicus* on the periphery (Woinarski *et al.*, 2000; Fox *et al.*, 2001). Other plant species include *Tecticornia indica* (Brown-headed samphire), *T. australasica* (grey samphire, purrawurrika) and *T. halocnemoides* (grey glasswort, purrawurrika). Coastal saltmarsh in northern Australia tend to have low floristic diversity, unlike southern locations (Rogers *et al.*, 2017).

Fauna

The mud flats support significant populations of migratory birds and shorebirds on the Tiwi Islands (Chatto, 2001, 2003), as is common in other areas of the Northern Territory (Delaney, 2012) and globally (Keith *et al.*, 2020). The saltmarsh is likely an important ecosystem for foraging, nursery grounds, and habitat for crabs, molluscs and crocodiles (Department of Environment and Climate Change, 2008; Creighton, Gillies and McLeod, 2015). Fish may move into the ecosystem with tides (Department of Environment and Climate Change, 2008; Keith *et al.*, 2020).

Potential threats

Threats to the coastal saltmarsh ecosystems in Australia primarily stem from changed hydrology, including flow rates, salinity and pollution, given the importance of hydrology in driving the ecosystem function (Finlayson *et al.*, 1999; Rogers *et al.*, 2017). Climate change will impact saltmarsh with sea level rise, changing rainfall and severe weather events increasing erosion (Finlayson *et al.*, 1999; Creighton, Gillies and McLeod, 2015; Rogers *et al.*, 2017). Coastal erosion is highly important to Tiwi People (Barnett *et al.*, 2023). Sea level rise may also cause the landward migration of mangrove species and encroachment into saltmarsh (Creighton, Gillies and McLeod, 2015; Murray *et al.*, 2019). Although not currently documented for the Tiwi Islands, anthropogenic impacts threaten coastal salt marsh and tidal flats globally (Department of Environment and Climate Change, 2008; Rogers *et al.*, 2017; Murray *et al.*, 2019). Anthropogenic impacts include modified tidal flows, developments and agriculture, pollution, and stormwater discharge (Finlayson *et al.*, 1999; Department of Environment and Climate Change, 2008; Creighton, Gillies and McLeod, 2015). Coastal saltmarsh is vulnerable to weed invasion, especially by salt-tolerant agricultural plants (Department of Environment and Climate Change, 2008; Creighton, Gillies and McLeod, 2015; Rogers *et al.*, 2017), although again not currently documented for the Tiwi Islands. The nationally-important *Mimosa pigra* (giant sensitive plant) weed does not appear to impact saltmarsh (Walden, 2004; Invasive Plants and Animals Committee, 2016).

Tiwi Islands ecosystem type	Global Ecosystem Typology ecosystem functional group (level 3)[1]	International Vegetation Classification formations (level 3)[2]	NVIS major vegetation group[3]	NVIS major vegetation sub-group[3]	Northern Territory vegetation map[4]	Northern Territory macrogroups[5]	Generalised vegetation types of the Tiwi Islands[6]	Tiwi Island vegetation map[7]
Coastal saltmarsh	MFT1.3 Coastal saltmarsh and reed-bed	MFT1.a3 Coastal saltmarsh & reedbed	22. Chenopod shrublands, samphire shrublands and forblands	39. Mixed chenopod, samphire +/- forbs 42. Naturally bare, sand, rock, claypan, mudflat	106. Saline tidal flats with scattered chenopod low shrubland (Samphire) 111. *Tecticornia* (Samphire) low open-shrubland	-	8. Samphire /saline coastal flat	Sand and salt flats

	fringing bare salt pans

[1] Keith, D. A., Ferrer-Paris, J. R., Nicholson, E., Bishop, M. J., Polidoro, B. A., Ramirez-Llodra, E., Tozer, M. G., Nel, J. L., Mac Nally, R., Gregr, E. J., Watermeyer, K. E., Essl, F., Faber-Langendoen, D., Franklin, J., Lehmann, C. E. R., Etter, A., Roux, D. J., Stark, J. S., Rowland, J. A., Brummitt, N.A., Fernandez-Arcaya, U.C., Suthers, I.M., Wiser, S.K., Donohue, I., Jackson, L.J., Pennington, R.T., Iliffe, T.M., Gerovasileiou, V., Giller, P., Robson, B.J., Pettorelli, N., Andrade, A., Lindgaard, A., Tahvanainen, T., Terauds, A., Chadwick, M.A., Murray, N.J., Moat, J., Pliscoff, P., Zager, I. and Kingsford, R. T. (2022). A function-based typology for Earth's ecosystems. Nature, 610(7932), Article 7932. https://doi.org/10.1038/s41586-022-05318-4

[2] Faber-Langendoen, D., Keeler-Wolf, T., Meidinger, D., Tart, D., Hoagland, B., Josse, C., Navarro, G., Ponomarenko, S., Saucier, J.-P., Weakley, A., & Comer, P. (2014). EcoVeg: A new approach to vegetation description and classification. Ecological Monographs, 84(4), 533–561. https://doi.org/10.1890/13-2334.1

[3] DCCEW. (2020). National Vegetation Information System (Version 6) [Computer software]. Australian Government. https://www.dcceew.gov.au/environment/land/native-vegetation/national-vegetation-information-system/data-products

[4] Wilson, B. A., Brocklehurst, P. S., Clark, M. J., & Dickonson, K. J. M. (1990). Vegetation survey ofthe Northern Territory, Australia, 1990. [Photos]. NT Map Shop.

[5] Hunter, J.T., Lewis, D., Addicott, E., Luxton, S., Cowie, I., Sparrow, B. and Leitch, E. (2022). A plot-based analysis of the vegetation of the Northern Territory, Australia: a first assessment within the International Vegetation Classification framework', Vegetation Classification and Survey, 3, pp. 161–174. Available at: https://doi.org/10.3897/VCS.83045.

[6] Brocklehurst, P., & Edmeades, B. (1998). Vegetation communities. In The history and natural resources of the Tiwi Islands, Northern Territory. Parks and Wildlife Commission of the Northern Territory.

[7] Woinarski, J. C. Z., Brennan, K., Cowie, I., Kerrigan, R., & Hempel, C. (2003). Biodiversity conservation on the Tiwi Islands, Northern Territory: Part 1. Environments and plants.

Table 16. Cross-reference of the coastal saltmarsh ecosystem to eight classification schemes spanning the global, national, state, and regional scales.

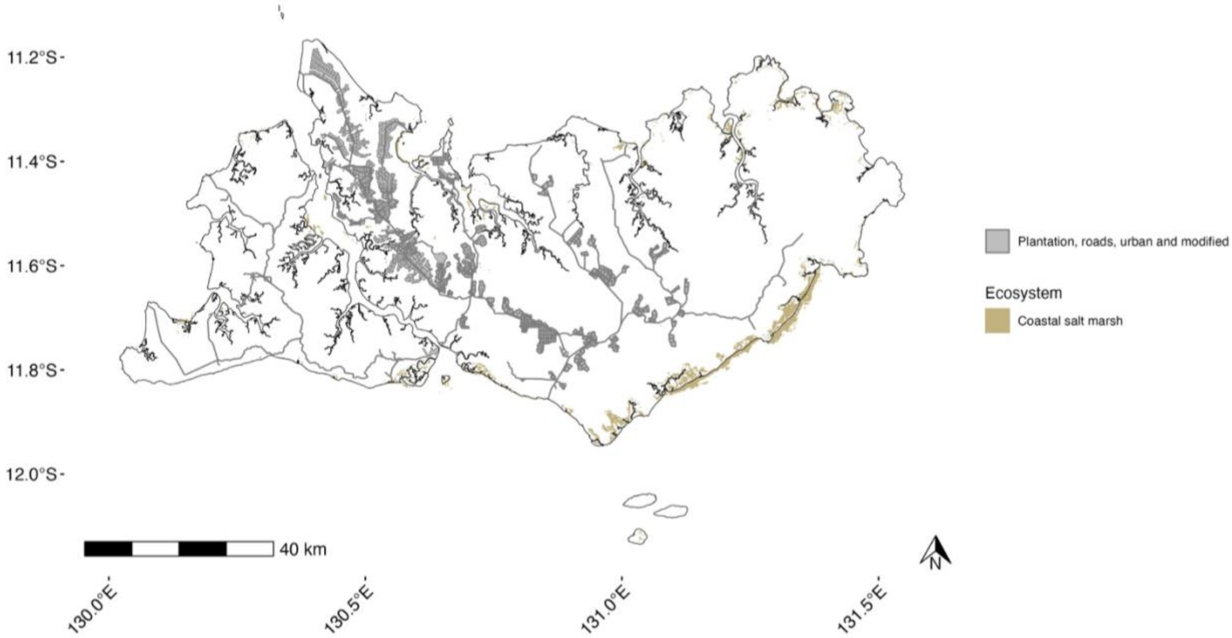


Figure 41. Map of the spatial distribution of the coastal saltmarsh and mud flats ecosystem on the Tiwi Islands, Australia.

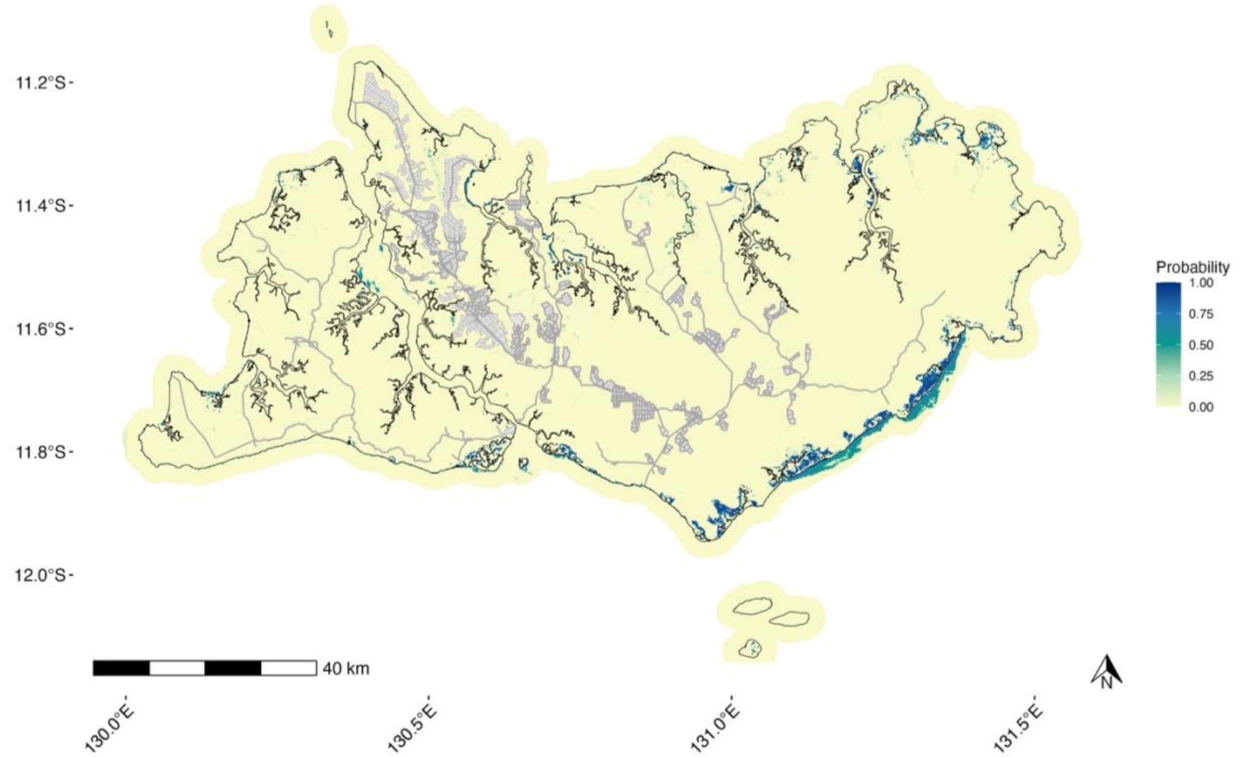


Figure 42. The prediction probability of the coastal saltmarsh and mud flats ecosystem on the Tiwi Islands, Australia from the random classification model.

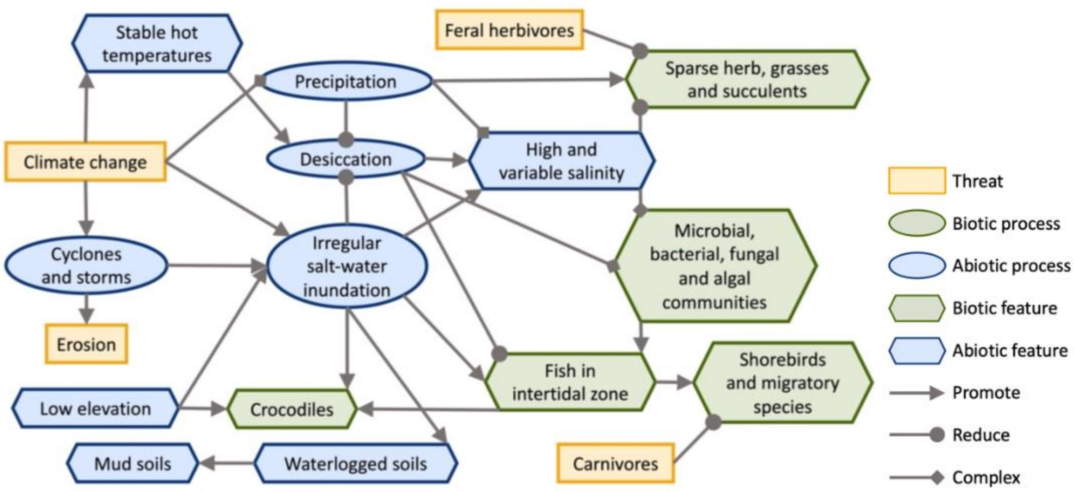


Figure 43. Cause-and-effect conceptual model based on the Red List of Ecosystem conceptual model structure for the coastal saltmarsh and mud flats ecosystem.

Figure 44. Images of the coastal saltmarsh and mud flats on the Tiwi Islands, Australia.

Sand dunes. Kurlimpiti.

Ecosystem function
Sand dune ecosystems (kurlimpiti in Tiwi Language) are unconsolidated beach sand sculpted into large dunes by the wind (Short and Woodroffe, 2009). On the Tiwi Islands, the dunes can be up to 50 m tall and are usually situated behind the coastal sandy beaches (Brocklehurst and Edmeades, 1998; Woinarski and Baker, 2002). Large dunes form with high wave action

moving sediment onshore, and strong onshore winds (Short and Woodroffe, 2009). The sand is an infertile and well-drained substrate limiting vegetation growth (Short and Woodroffe, 2009). The dune ecosystem exhibits high soil salt content due to ocean spray and experiences strong winds and severe weather events (Short and Woodroffe, 2009; Keith *et al.*, 2020).

Geographical extent

There are large areas of coastal dune complexes on the Tiwi Islands, with notably large areas on the south-western coastline of Bathurst Island (Brocklehurst and Edmeades, 1998; Woinarski and Baker, 2002; Woinarski, Brennan, Cowie, *et al.*, 2003), e.g., at Port Hurd, Bathurst Island. Other island-wide classification systems and mapping for the Tiwi islands did not explicitly recognise sand dunes (Fensham, 1993). There are extensive sand dunes around Australia and other regions of the Northern Territory (Clark, Fischer and Hunter, 2021).

Flora

Swaths of bare sand intermingle with sparely grassed areas (DCCEEW, 2020). On the Tiwi Islands, common plant species include *Spinifex longifolius (*pitarika), scatted shrubs of *Acacia* sp., and trees of bloodwood eucalypts, which form a sparsely vegetated matrix (Brocklehurst and Edmeades, 1998). A small grass on the sand dune is called mulani in Tiwi. Other common plants are the herbs *Ipomoea pes-caprae* (Beach morning glory, rokuni*), Fimbristylis sericea, and Canavalia rosea (tingatiyanganila), and the shrub Scaevola taccada (wuraka). The plant I. pes-caprae* is collected for medicines (Thompson *et al.*, 2019). Tiwi knowledge holders described collecting pinyama (wild apple) from the sand dunes during our research. The coastal casuarina (*Casuarina equisetifolia*, munkarajinga/munkuraji*)* likely afforded protection from fire by the sandy substrate. The sand dunes also support two species of conservation significance with the near threatened in the Northern Territory *Triumfetta aquila* and *T. repens* (Woinarski, Brennan, Cowie, *et al.*, 2003). Vegetation cover on dunes decreases with low rainfall (Clark, Fischer and Hunter, 2021). Inland, sandy dunes become vegetated and grade into numerous other vegetation types, thought to be related to soil moisture gradients (Fensham, 1993; Brocklehurst and Edmeades, 1998; Hollingsworth *et al.*, 2006). Dunes vegetation cover and productivity may increase with climate change (Clark, Fischer and Hunter, 2021).

Fauna

Little is documented about the fauna in sand dune ecosystems on the Tiwi Islands. Vertebrate species likely use dunes for selected resources rather than solely inhabiting the dunes. Animal tracks are clear on the sand. Sand tracking is a traditional hunting method used by other Indigenous groups in Australia.

Potential threats

Dunes are dynamic systems that naturally erode and recover (Clark, Fischer and Hunter, 2021). However, severe weather events exacerbate natural erosion rates (Clark, Fischer and Hunter, 2021). Dunes are also vulnerable to sea level rise and ocean acidification (Clark, Fischer and Hunter, 2021). Vegetation cover on dunes decreases during periods with low rainfall (Clark, Fischer and Hunter, 2021), leaving the dunes more susceptible to increased erosion. On the Tiwi Islands, sand mining would also cause direct and indirect impacts to the ecosystem (EcOz Environmental Services, 2012). In other regions of Australia, coastal dunes are degraded by human traffic and invasive species (Clark, Fischer and Hunter, 2021).

Table 17. Cross-reference of the sand dune ecosystem across eight classification schemes from global, national, state, and regional scales.

Tiwi Islands ecosystem type	Global Ecosystem Typology ecosystem functional group (level 3)[1]	International Vegetation Classification formations (level 3)[2]	NVIS major vegetation group[3]	NVIS major vegetation sub-group[3]	Northern Territory vegetation map[4]	Northern Territory macrogroups[5]	Generalised vegetation types of the Tiwi Islands[6]	Tiwi Island vegetation map[7]
Sand dunes	MT2.1 Coastal shrublands and grasslands	MT2.a1 Coastal marine shrubland & grassland	21. Other grasslands, herblands, sedgelands and rushlands	64. Other grasslands	102. Coastal dune complex	-	7. Beaches/chenier ridges/grasslands	Partially included in 'sand and salt flats'
							7a. Low *Corymbia foelscheana* open-forest	
			27. Naturally bare - sand, rock, claypan, mudflat	42. Naturally bare - sand, rock, claypan, mudflat			7b. Low *Acacia difficilis* & *Terminalia ferdinandiana* open-woodland	
							7c. Low *T. ferdinandiana* open-forest	

1 Keith, D. A., Ferrer-Paris, J. R., Nicholson, E., Bishop, M. J., Polidoro, B. A., Ramirez-Llodra, E., Tozer, M. G., Nel, J. L., Mac Nally, R., Gregr, E. J., Watermeyer, K. E., Essl, F., Faber-Langendoen, D., Franklin, J., Lehmann, C. E. R., Etter, A., Roux, D. J., Stark, J. S., Rowland, J. A., Brummitt, N.A., Fernandez-Arcaya, U.C., Suthers, I.M., Wiser, S.K., Donohue, I., Jackson, L.J., Pennington, R.T., Iliffe, T.M., Gerovasileiou, V., Giller, P., Robson, B.J., Pettorelli, N., Andrade, A., Lindgaard, A., Tahvanainen, T., Terauds, A., Chadwick, M.A., Murray, N.J., Moat, J., Pliscoff, P., Zager, I. and Kingsford, R. T. (2022). A function-based typology for Earth's ecosystems. *Nature*, *610*(7932), Article 7932. https://doi.org/10.1038/s41586-022-05318-4

2 Faber-Langendoen, D., Keeler-Wolf, T., Meidinger, D., Tart, D., Hoagland, B., Josse, C., Navarro, G., Ponomarenko, S., Saucier, J.-P., Weakley, A., & Comer, P. (2014). EcoVeg: A new approach to vegetation description and classification. *Ecological Monographs*, *84*(4), 533–561. https://doi.org/10.1890/13-2334.1

3 DCCEW. (2020). *National Vegetation Information System* (Version 6) [Computer software]. Australian Government. https://www.dcceew.gov.au/environment/land/native-vegetation/national-vegetation-information-system/data-products

4 Wilson, B. A., Brocklehurst, P. S., Clark, M. J., & Dickonson, K. J. M. (1990). *Vegetation survey of the Northern Territory, Australia, 1990.* [Photos]. NT Map Shop.

5 Hunter, J.T., Lewis, D., Addicott, E., Luxton, S., Cowie, I., Sparrow, B. and Leitch, E. (2022). A plot-based analysis of the vegetation of the Northern Territory, Australia: a first assessment within the International Vegetation Classification framework', *Vegetation Classification and Survey*, 3, pp. 161–174. Available at: https://doi.org/10.3897/VCS.83045.

6 Brocklehurst, P., & Edmeades, B. (1998). Vegetation communities. In *The history and natural resources of the Tiwi Islands, Northern Territory.* Parks and Wildlife Commission of the Northern Territory.

7 Woinarski, J. C. Z., Brennan, K., Cowie, I., Kerrigan, R., & Hempel, C. (2003). *Biodiversity conservation on the Tiwi Islands, Northern Territory: Part 1. Environments and plants* (1).

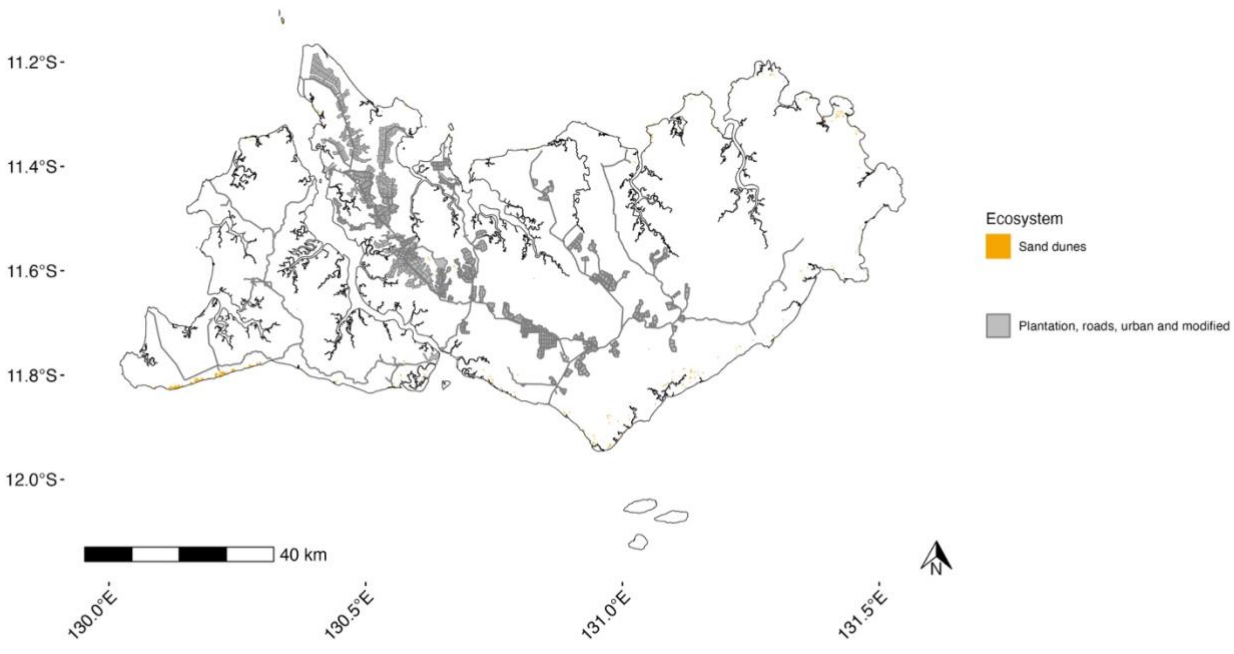


Figure 45. Map of the spatial distribution of the sand dune ecosystem on the Tiwi Islands, Australia.

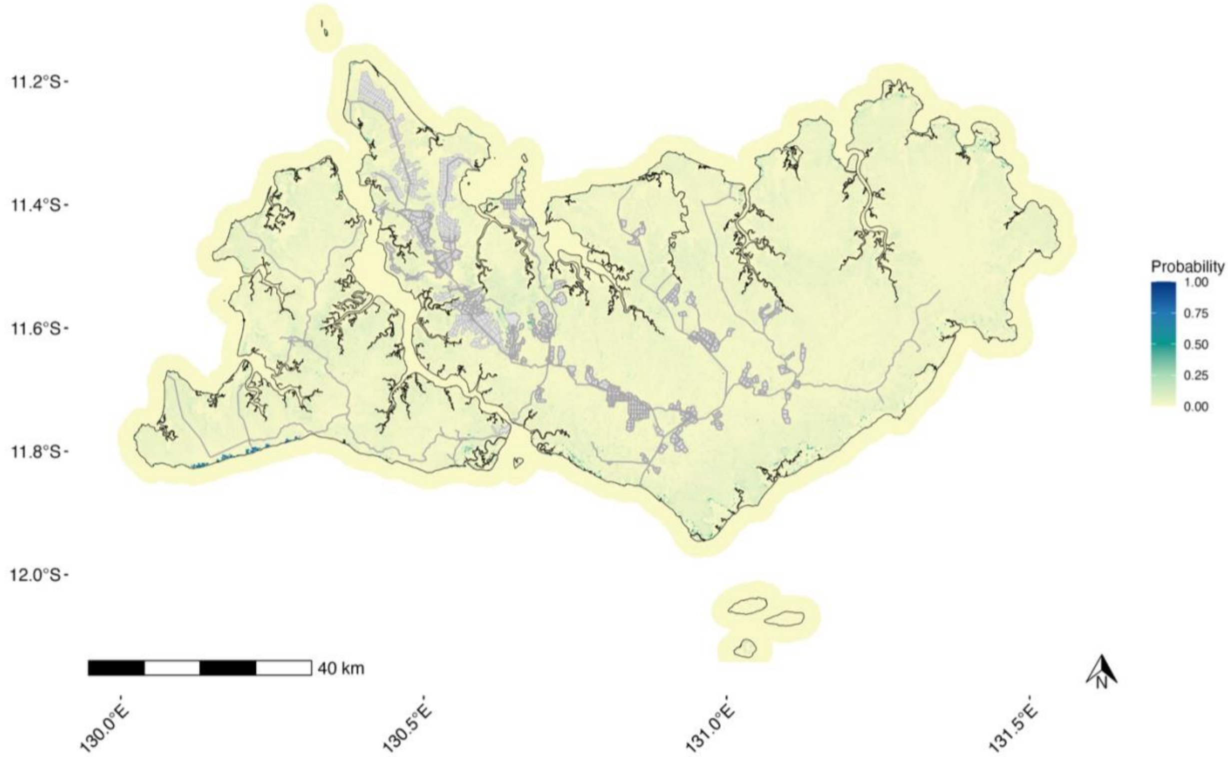


Figure 46. The prediction probability of the sand dune ecosystem on the Tiwi Islands, Australia from the random classification model.

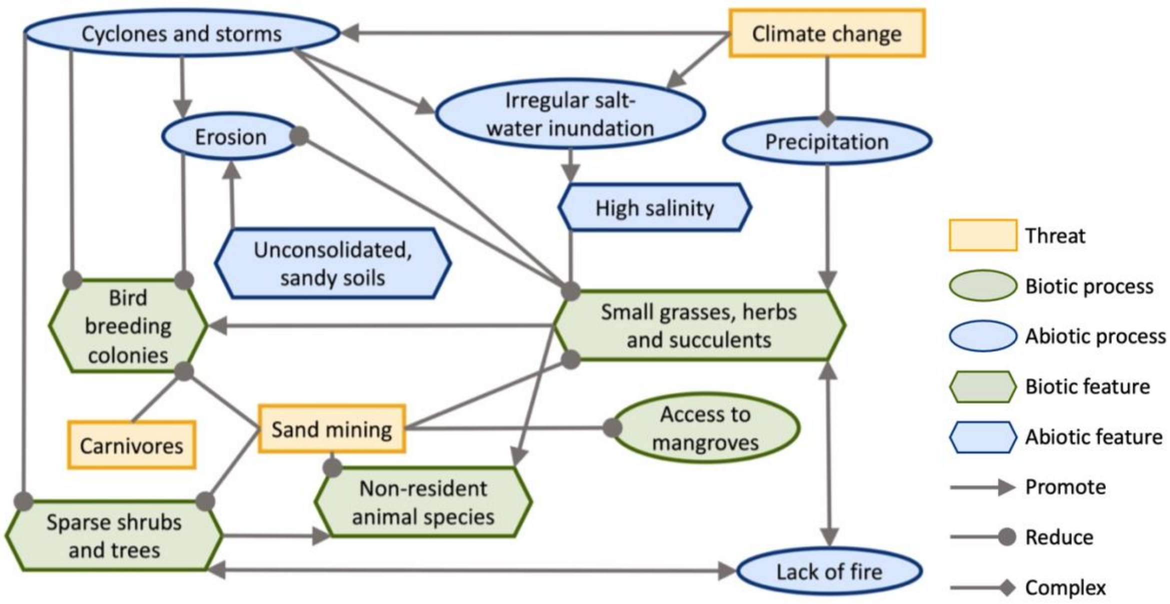


Figure 47. Cause-and-effect conceptual model based on the Red List of Ecosystem conceptual model structure for the sand dune ecosystem.

Figure 48. Images of the sand dune ecosystem on the Tiwi Islands, Australia.

Sandy beaches and shorelines. Tingata.

Ecosystem function

Sandy shorelines and beaches (tingata in Tiwi Language) are an intertidal ecosystem at the boundary between the ocean and the land characterised by a sandy substrate (Keith *et al.*, 2022). Beaches occur at low elevations and receive high salt inputs, regular inundation and wave disturbance from the ocean (Keith *et al.*, 2020). The beaches, sand bars (rapatinga) and spits move and erode regularly with the wave action (Barnett *et al.*, 2023).

Geographical extent

On the Tiwi Islands, there are large expanses of sandy beaches across both islands (Woinarski *et al.*, 2000). Sandy shorelines have been recorded on the Tiwi Islands near Milikapiti and Pirlangimpi (Barnett *et al.*, 2023) and visited with Tiwi people during this research on the southern and south-western coasts of Bathurst Island and on the south-western coast of Melville Island. Sandy beaches are extensive across the Northern Territory, around Australia, and globally (Short and Woodroffe, 2009; Clark, Fischer and Hunter, 2021; Keith *et al.*, 2022).

Flora

These beaches are naturally predominantly unvegetated (DCCEEW, 2020), with the occurrence of herbs, grasses and succulents increasing inland (e.g. *Sporobolus virginicus*, *Ipomoea pes-caprae* (Beach morning glory, rokuni), *Tribulus cistoides*, *Canavalia rosea*, *Sesuvium portulacastrum* (Woinarski, Brennan, Cowie, *et al.*, 2003).

Fauna

Beaches are a crucial ecosystem for a wide range of fauna. Sandy beaches are important breeding grounds for turtles which nest on the upper reaches of the beach (Northern Territory Government, 2018). Turtle species on the Tiwi Islands are olive ridley (endangered$_{AUS,}$ vulnerable$_{NT}$, *Lepidochelys olivacea*), green turtle (vulnerable$_{AUS}$, *Chelonia mydas*, kitirika/jarrakalani), hawksbill turtle (vulnerable$_{AUS, NT}$, *Eretmochelys imbricata*, manjidi/marrakani), flatback turtle (vulnerable$_{AUS}$, *Natator depressus*) and loggerhead turtle (endangered$_{AUS,}$ vulnerable$_{NT}$, *Caretta caretta*, yirruwamini/jarrakalani) (Woinarski *et al.*, 2000; Woinarski, Brennan, Cowie, *et al.*, 2003; Woinarski, Brennan, Hempel, *et al.*, 2003; Department of Environment, Parks and Water Security, 2021i, 2021f, 2021m). The largest colonies of the olive ridley turtle nest on Melville Island, particularly near Andranangoo Creek West and Leathbridge Bay West (EcOz Environmental Services, 2012). Southwestern Bathurst Island and northern Melville Island support flatback turtles (Woinarski and Baker, 2002). Globally significant aggregations of migratory wader breeding colonies feed and nest on the Tiwi Islands, particularly on Seagull Island (Chatto, 2001), particularly greater crested terns (*Thalasseus bergii*, martapani) alongside smaller populations of black-naped tern, other bird species (Woinarski *et al.*, 2000; Woinarski, Brennan, Hempel, *et al.*, 2003). Seagull Island also supports large populations of turtles, according to Tiwi Knowledge Holders and Tiwi rangers. Tiwi people collect eggs from the terns for food. Beaches are also used for fishing, hunting mud crabs (kurumpuka/wurlanga), collecting turtle eggs, accessing mangroves for collecting food, and harvesting medicines from the *I. pes-caprae* and tarripilima (germinated *Rhizophora* seeds) (TLC *et al.*, 2001; Thompson *et al.*, 2019).

Potential threats

Tiwi people are concerned about the loss of sandy beaches through erosion and rising sea levels which threatens infrastructure near the communities (Barnett *et al.*, 2023). The increased frequency and severity of storm events with climate change will also exacerbate erosion (Clark, Fischer and Hunter, 2021). Similarly, rising sea levels and storm events may threaten turtle nests. Tiwi people also described pigs and dingos excavating and consuming turtle nests as an issue for the turtles on the Tiwi Islands, as observed in other areas of Australia (Whytlaw, Edwards and Congdon, 2013). Pollution may also degrade sand beaches (Clark, Fischer and Hunter, 2021). In other areas of Australia, coastal development and land clearing have threatened beaches historically (Clark, Fischer and Hunter, 2021).

Table 18. Cross-reference of the sandy shorelines ecosystem to eight classification schemes spanning the global, national, state, and regional scales.

Tiwi Islands ecosystem type	Global Ecosystem Typology ecosystem functional group (level 3)[1]	International Vegetation Classification formations (level 3)[2]	NVIS major vegetation group[3]	NVIS major vegetation sub-group[3]	Northern Territory vegetation map[4]	Northern Territory macrogroups[5]	Generalised vegetation types of the Tiwi Islands[6]	Tiwi Island vegetation map[7]
Sandy shorelines	MT1.a3 Sandy shore	MT1.a3 Sandy Shore	27. Naturally bare - sand, rock, claypan, mudflat	41. Naturally bare - sand, rock, claypan, mudflat	-	-	7. beaches/chenier ridges/grasslands	Sand and salt flats

[1] Keith, D. A., Ferrer-Paris, J. R., Nicholson, E., Bishop, M. J., Polidoro, B. A., Ramirez-Llodra, E., Tozer, M. G., Nel, J. L., Mac Nally, R., Gregr, E. J., Watermeyer, K. E., Essl, F., Faber-Langendoen, D., Franklin, J., Lehmann, C. E. R., Etter, A., Roux, D. J., Stark, J. S., Rowland, J. A., Brummitt, N.A., Fernandez-Arcaya, U.C., Suthers, I.M., Wiser, S.K., Donohue, I., Jackson, L.J., Pennington, R.T., Iliffe, T.M., Gerovasileiou, V., Giller, P., Robson, B.J., Pettorelli, N., Andrade, A., Lindgaard, A., Tahvanainen, T., Terauds, A., Chadwick, M.A., Murray, N.J., Moat, J., Pliscoff, P., Zager, I. and Kingsford, R. T. (2022). A function-based typology for Earth's ecosystems. *Nature*, *610*(7932), Article 7932. https://doi.org/10.1038/s41586-022-05318-4

[2] Faber-Langendoen, D., Keeler-Wolf, T., Meidinger, D., Tart, D., Hoagland, B., Josse, C., Navarro, G., Ponomarenko, S., Saucier, J.-P., Weakley, A., & Comer, P. (2014). EcoVeg: A new approach to vegetation description and classification. *Ecological Monographs*, *84*(4), 533–561. https://doi.org/10.1890/13-2334.1

[3] DCCEW. (2020). *National Vegetation Information System* (Version 6) [Computer software]. Australian Government. https://www.dcceew.gov.au/environment/land/native-vegetation/national-vegetation-information-system/data-products

[4] Wilson, B. A., Brocklehurst, P. S., Clark, M. J., & Dickonson, K. J. M. (1990). *Vegetation survey of the Northern Territory, Australia, 1990.* [Photos]. NT Map Shop.

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[6] Brocklehurst, P., & Edmeades, B. (1998). Vegetation communities. In *The history and natural resources of the Tiwi Islands, Northern Territory.* Parks and Wildlife Commission of the Northern Territory.

[7] Woinarski, J. C. Z., Brennan, K., Cowie, I., Kerrigan, R., & Hempel, C. (2003). *Biodiversity conservation on the Tiwi Islands, Northern Territory: Part 1. Environments and plants*.

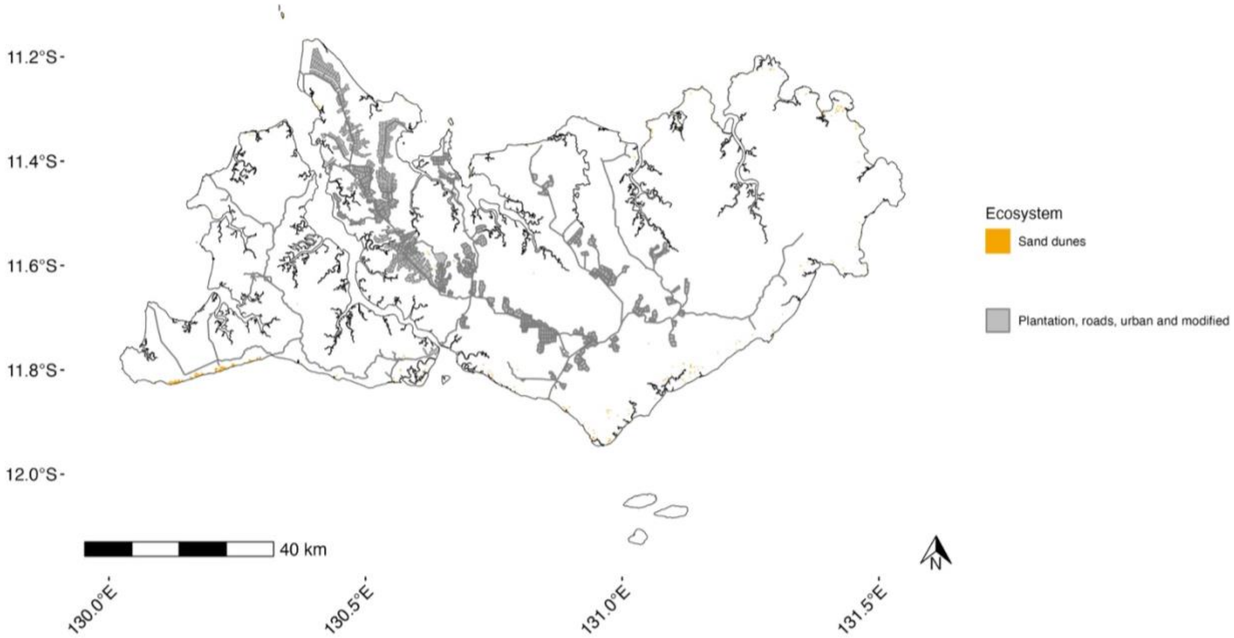

Figure 49. Map of the spatial distribution of the sandy shorelines ecosystem on the Tiwi Islands, Australia.

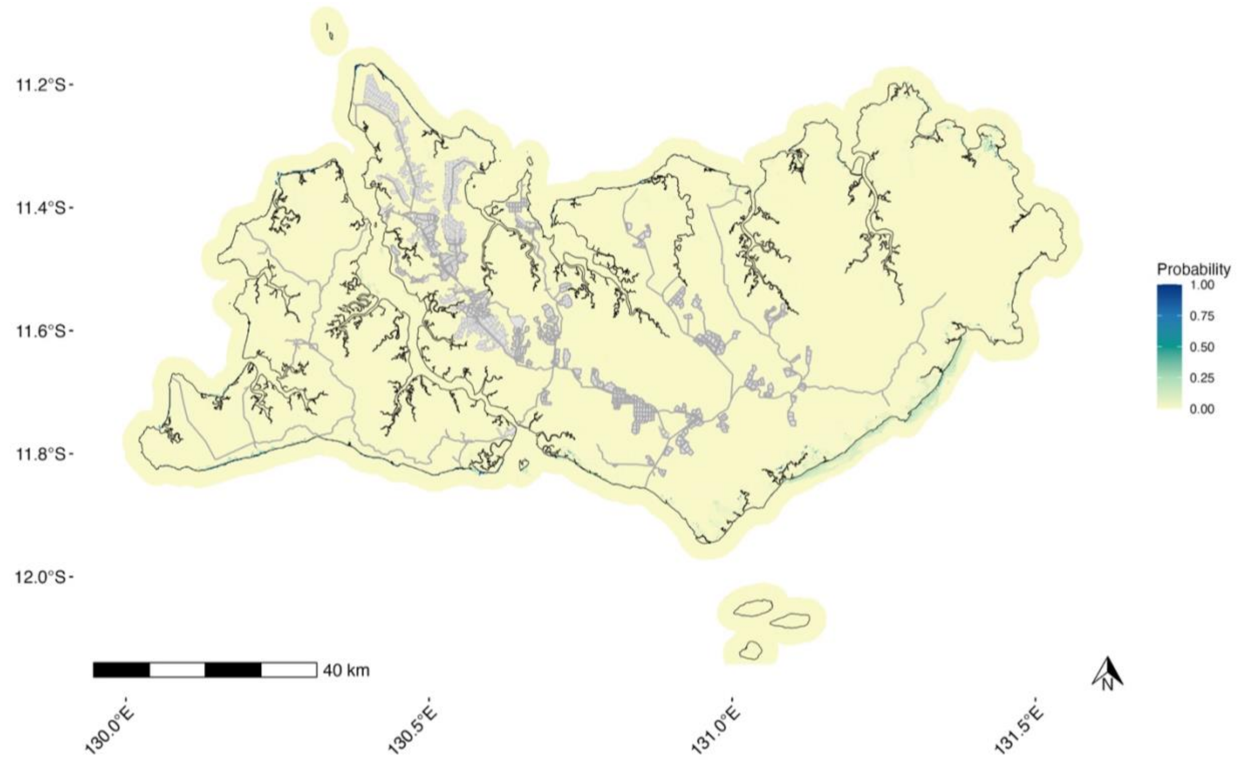

Figure 50. The prediction probability of the sandy shorelines ecosystem on the Tiwi Islands, Australia from the random classification model.

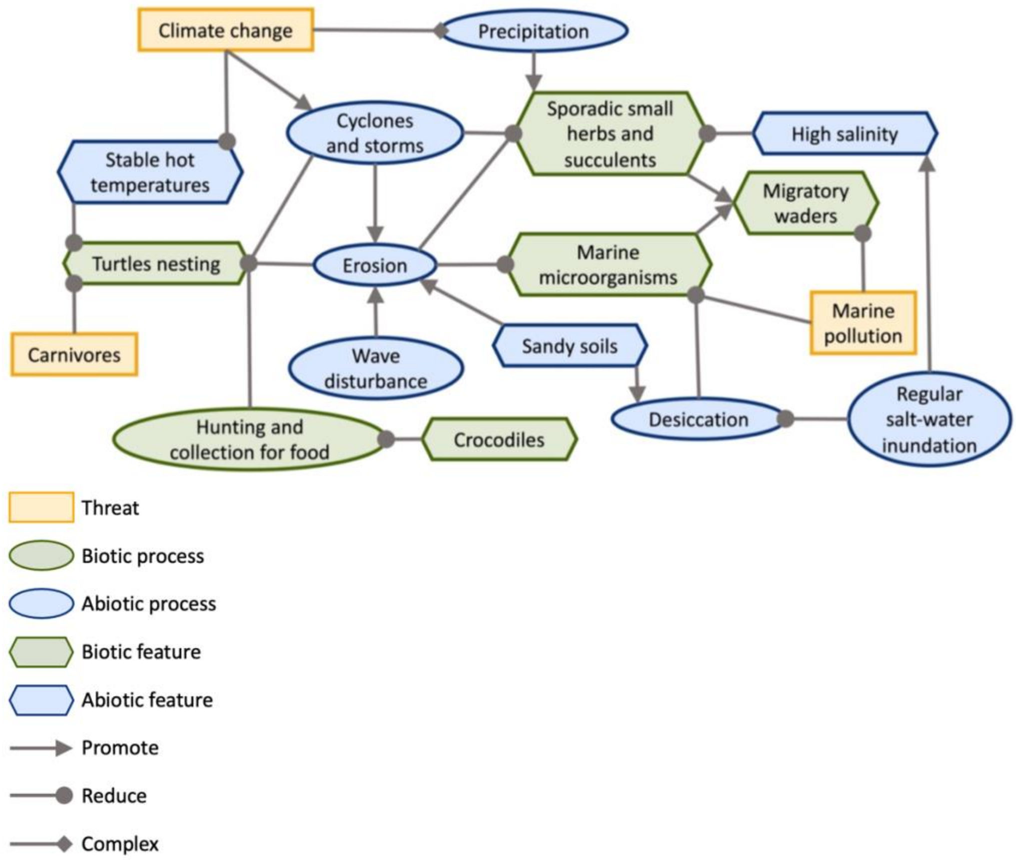

Figure 51. Cause-and-effect conceptual model based on the Red List of Ecosystem conceptual model structure for the sandy shorelines ecosystem.

Figure 52. Images of the sandy shorelines ecosystem on the Tiwi Islands, Australia.

Rocky shoreline.

Ecosystem function

Rocky shorelines are an intertidal ecosystem at the boundary between the ocean and the land, characterised by the presence of rocks (Short and Woodroffe, 2009; Keith *et al.*, 2020). Wave disturbance, wind, tidal inundation and desiccation create fine-scale stress gradients and drive the biotic community structure (Short and Woodroffe, 2009; Keith *et al.*, 2020). The complex rock shapes create microrefugia from these stressors (Keith *et al.*, 2020; Clark, Fischer and Hunter, 2021).

Geographic distribution

Rocky shorelines and headlands have been recorded on the Tiwi Islands near Milikapiti (Barnett *et al.*, 2023) and visited with Tiwi people during this research on the southern and south-western coasts of Bathurst Island on Jikaluruwu clan lands. While rocky shorelines were visited with Tiwi knowledge holders during this research, we did not collect enough locations to map the rocky areas from satellite imagery with a classification model. Given the distinctive colour of the rocks, it would be possible to undertake localised surveys using drones or obtain fine-scale satellite imagery (e.g. <2m resolution) to map the rocky shorelines (Clark, Fischer and Hunter, 2021). Rocky shorelines occur in other regions of the Northern

Territory, such as near Darwin and in Arnhem land, around Australia (Short and Woodroffe, 2009; Clark, Fischer and Hunter, 2021) and globally (Keith *et al.*, 2022).

Flora and fauna

Rocky shorelines provide habitat and protection from strong environmental stressors to many species (Clark, Fischer and Hunter, 2021). Algae cover the rocky substrate in inundated areas, providing food resources and cover to the fauna, including molluscs and crustaceans (Keith *et al.*, 2020). Fish and birds consume a variety of prey (Keith *et al.*, 2020). Tiwi people describe the rocky shorelines as useful for fishing, capturing mud crabs, and collecting oysters (TLC *et al.*, 2001). There is no published information regarding the community composition, ecosystem function, nor locations the rocky shorelines of the Tiwi Islands. Less is known about the rocky shores in tropical areas compared to other areas of Australia (Short and Woodroffe, 2009).

Potential threats

Erosion and sedimentation threaten to rocky shorelines in the Northern Territory (Northern Territory Government, 2018), although some level of erosion is a natural (Short and Woodroffe, 2009). High erosion rates on the Tiwi Islands is exposing an increased number and amount of rocks (Barnett *et al.*, 2023). Climate change affects rocky shorelines through warmer air and water temperatures, sea level rise, ocean acidification, and extreme weather events such as storms and cyclones (Northern Territory Government, 2018; Clark, Fischer and Hunter, 2021). Pollution, including chemicals and fuel, would also harm the shoreline biota (Northern Territory Government, 2018). In other regions of Australia, rocky shorelines are affected by trampling, poor water quality, and urban development (Clark, Fischer and Hunter, 2021).

Table 19. Cross-reference of the rocky shoreline ecosystem to eight classification schemes spanning the global, national, state and region scale.

Tiwi Islands ecosystem type	Global Ecosystem Typology ecosystem functional group (level 3)[1]	International Vegetation Classification formations (level 3)[2]	NVIS major vegetation group[3]	NVIS major vegetation sub-group[3]	Northern Territory vegetation map[4]	Northern Territory macrogroups[5]	Generalised vegetation types of the Tiwi Islands[6]	Tiwi Island vegetation map[7]
Rocky shorelines	Rocky shorelines	MT1.a1 Marine shorelines	MT1.a1 Rocky Shore	27. Naturally bare, sand, rock, claypan, mudflat	42. Naturally bare, sand, rock, claypan, mudflat	-	-	-

[1] Keith, D. A., Ferrer-Paris, J. R., Nicholson, E., Bishop, M. J., Polidoro, B. A., Ramirez-Llodra, E., Tozer, M. G., Nel, J. L., Mac Nally, R., Gregr, E. J., Watermeyer, K. E., Essl, F., Faber-Langendoen, D., Franklin, J., Lehmann, C. E. R., Etter, A., Roux, D. J., Stark, J. S., Rowland, J. A., Brummitt, N.A., Fernandez-Arcaya, U.C., Suthers, I.M., Wiser, S.K., Donohue, I., Jackson, L.J., Pennington, R.T., Iliffe, T.M., Gerovasileiou, V., Giller, P., Robson, B.J., Pettorelli, N., Andrade, A., Lindgaard, A., Tahvanainen, T., Terauds, A., Chadwick, M.A., Murray, N.J., Moat, J., Pliscoff, P., Zager, I. and Kingsford, R. T. (2022). A function-based typology for Earth's ecosystems. *Nature*, *610*(7932), Article 7932. https://doi.org/10.1038/s41586-022-05318-4

[2] Faber-Langendoen, D., Keeler-Wolf, T., Meidinger, D., Tart, D., Hoagland, B., Josse, C., Navarro, G., Ponomarenko, S., Saucier, J.-P., Weakley, A., & Comer, P. (2014). EcoVeg: A new approach to vegetation description and classification. *Ecological Monographs*, *84*(4), 533–561. https://doi.org/10.1890/13-2334.1

[3] DCCEW. (2020). *National Vegetation Information System* (Version 6) [Computer software]. Australian Government. https://www.dcceew.gov.au/environment/land/native-vegetation/national-vegetation-information-system/data-products

[4] Wilson, B. A., Brocklehurst, P. S., Clark, M. J., & Dickonson, K. J. M. (1990). *Vegetation survey ofthe Northern Territory, Australia, 1990.* [Photos]. NT Map Shop.

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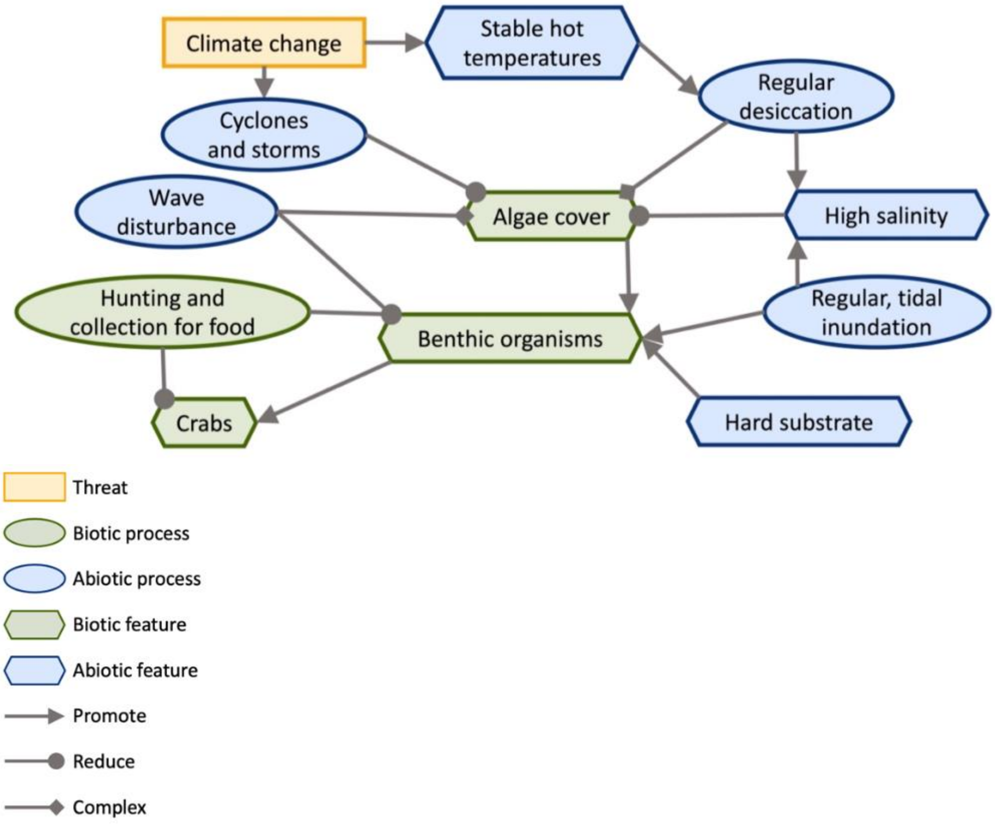

Figure 53. Cause-and-effect conceptual model based on the Red List of Ecosystem conceptual model structure for the rocky shorelines ecosystem.

Figure 54. Images of the rocky shoreline ecosystem on the Tiwi Islands, Australia.

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Appendix S8 – Cross-reference between the classification schemes

Table 20. Cross-reference between vegetation and ecosystem classification schemes from global, national, and regional levels on the Tiwi Islands, Australia.

Tiwi Island ecosystem types from this research	Words in Tiwi language	IUCN Global Ecosystem Typology (Keith *et al.*, 2022)			International Vegetation Classification (Faber-Langendoen *et al.*, 2014)			National Vegetation Information System (DCCEEW, 2020)	
		Realm	**Biome**	**Ecosystem function group**	**L1 Biome class**	**L2 Biome subclass**	**L3 Formation**	**Major vegetation groups**	**Major vegetation subgroups**
Scale of relevancy									
Regional (Tiwi Islands)	Regional (Tiwi Islands)	Global	Global	Global	Global	Global	Global	National (Australia)	National (Australia)
Attributes used to define the classes									
Structure and processes		Environmental processes and drivers						Structure, dominant genera and floristics using Specht (1970), Specht *et al.*, (1974) and Walter Hopkins (1990).	
Ecosystem types									
Eucalypt open forest savanna	*Warta*	T: Terrestrial	T4 Savannas and grasslands	T4.2 Pyric tussock savanna	T3 Savanna, grassland & shrubland	T3.a. Tropical savanna	T3.a1Tropical savanna	3. Eucalypt open forests	4. Eucalyptus open forests with a shrubby understorey 5. Eucalypt open forest with grassy understory 7. Tropical *Eucalyptus* Forest and woodlands with a tall annual grassy understorey 9. *Eucalyptus* woodlands with a tussock grass understorey
Eucalypt and mixed species savanna	*Warta*	T: Terrestrial	T4 Savannas and grasslands	T4.2 Pyric tussock savanna	T3 Savanna, grassland & shrubland	T3.a. Tropical savanna	T3.a1Tropical savanna	12. Tropical Eucalypt woodlands/grasslands	7. Tropical Eucalyptus open forests and woodlands with a tall annual grassy understory 8. Eucalyptus woodlands with a shrubby understorey 9. Eucalypt woodland with tussock grass understorey 19. Eucalyptus low open woodlands with tussock grass 48. Eucalypt open woodland with grass understorey
Treeless plains	*Muriyini*	T: Terrestrial	T3 Shrublands and shrubby woodlands	T3.1 Seasonally dry tropical shrubland	T3 Savanna, grassland & shrubland	T3.b Tropical shrubland	T3.b2 Seasonally dry tropical shrubland	16. *Acacia* shrublands	21. Other *Acacia* tall open shrublands and [tall] shrublands
								13. *Acacia* open woodlands 6. *Acacia* forests and woodlands	24. *Acacia* (+/- low) open woodlands and sparse shrublands (+/-) tussock grass
								17. Other shrublands	28. Low closed forest or tall closed shrublands (including *Acacia*, *Melaleuca* and *Banksia*) 49. *Melaleuca* shrublands and open shrublands
Wet monsoonal rainforest	*Yawurlama* (jungle) *Kukuni* (freshwater) *Jakularma*	T: Terrestrial	T1 Topical-subtropical forests	T1.1 Tropical/subtropical lowland rainforest	T1. Tropical forest	T1.a Tropical rainforest	T1.a1 Tropical lowland rainforest	1. Rainforests and vine thickets	2. Tropical or sub-tropical rainforest
Dry rainforest and vine thickets	*Yawurlama* (jungle) *Jakularma*	T: Terrestrial	T1 Topical-subtropical forests	T1.2 Tropical/subtropical dry forest and thickets	T1. Tropical forest	T1.b Tropical dry forest	T1b.4 Tropical seasonally dry forest & thicket	1. Rainforests and vine thickets	62. Dry rainforest or vine ticket
Melaleuca savanna	*Punkaringa* (paperbark trees)	T: Terrestrial	T4 Savannas and grasslands	T4.2 Pyric tussock savanna	T3 Savanna, grassland & shrubland	T3.a. Tropical savanna	T3.a1Tropical savanna	31. Other open woodlands	75. *Melaleuca* open woodlands
								17. Other shrublands	49. *Melaleuca* shrublands and open shrublands.
Grasslands and sedgeland swamp	*Turringiya*	TF: Terrestrial - Freshwater	TF1 Palustrine wetlands	TF1.4 Seasonal floodplain marshes	TF1. Palustrine wetland	TF1.b Marsh, Wet meadow, & shrub wetland	TF1.b3 Marsh, wet meadow & shrub wetland	21. Other Grasslands, Herblands, Sedgelands and Rushlands	38. Wet tussock grassland with herbs, sedges or rushes, herblands or ferns 63. Sedgelands, rushes or reeds
Mangroves	*Mirriparinga* *Pamparinga*	MFT: Marine – Freshwater – Terrestrial	MFT1 Brackish tidal	MFT 1.2 Intertidal forests and shrublands	MFT1. Brackish tidal wetland	MFT1.a Brackish tidal wetland	MFT1.a2 Mangrove	23. Mangroves	40. Mangroves

Coastal saltmarsh	*Yarti* (open places)	MFT: Marine – Freshwater – Terrestrial	MFT1 Brackish tidal	MFT1.3 Coastal saltmarsh and reed-bed	MFT1. Brackish tidal wetland	MFT1.a Brackish tidal wetland	MFT1.a3 Coastal saltmarsh & reedbed	22. Chenopod shrublands, samphire shrublands and forblands	39. Mixed chenopod, samphire +/- forbs
									42. Naturally bare, sand, rock, claypan, mudflat
Sand dunes	*Kurlimipiti* *Pungamparna*	MT: Marine – Terrestrial	MT2 Supralittoral coastal	MT2.1 Coastal shrublands and grasslands	MT2. Supralittoral marine coast	MT2.a Supralittoral marine coast	MT2.a1 Coastal marine shrubland & grassland	21. Other grasslands, herblands, sedgelands and rushlands	64. Other grasslands
								27. Naturally bare - sand, rock, claypan, mudflat	42. Naturally bare, sand, rock, claypan, mudflat
Sandy beaches and shorelines	*Tingata* *Wurrungalama*, *Yartila*, *Kuluwunila* (beach, when dry) *Rapatinga* (sandbar)	MT: Marine – Terrestrial	MT1 shorelines	MT1.3 Sandy shore	MT1. Marine shoreline	MT1.a Marine-intertidal shoreline	MT1.a3 Sandy shore	27. Naturally bare - sand, rock, claypan, mudflat	42. Naturally bare, sand, rock, claypan, mudflat
Rocky shorelines	-	MT: Marine – Terrestrial	MT1 shorelines	MT1.1 Rocky shore	MT1. Marine shoreline	MT1.a Marine-intertidal shoreline	MT1.a1 Rocky shore	27. Naturally bare - sand, rock, claypan, mudflat	42. Naturally bare, sand, rock, claypan, mudflat
Ocean	*Winga* (ocean) *Juwurti* (deep water) *Mirripakarma*	M: Marine	-	-	-	-	-	28. Sea and estuaries	46. Sea, estuaries (includes seagrass)
Freshwater and brackish rivers, streams and waterfalls	*Yirringarni* (waterhole, lake, lagoon) *Kilinjini* (waterhole, lake, billabong, swamp)	FM: Freshwater - Marine	FM1 Semi-confined transitional waters	FM1.2 Permanently open riverine estuaries and bays	-	-	-	28. Sea and estuaries	46. Sea, estuaries (includes seagrass)
		F: Freshwater	F1 Rivers and streams	F1.4 Seasonal upland streams	-	-	-	24. Inland Aquatic - freshwater, salt lakes, lagoons	44. Freshwater, dams, lakes, lagoons, or aquatic plants
				F1.5 Seasonal lowland rivers	-	-	-		
Communities and modified	-	T: Terrestrial	T7 Intensive land-use	T7.4 Urban industrial	T7. Intensive land-use	T7.b Developed land	T7.b4 Urban and infrastructure land	25. Cleared, non-native vegetation, building	98. Cleared, non-native vegetation, building
				T7.5 semi-natural pastures and old fields	-	-	-	29. Regrowth, modified native vegetation	90. Regrowth or modified forests and woodlands
									91. Regrowth or modified shrublands
		MT: Marine - Terrestrial	MT3 Anthropogenic shorelines	MT3.1 Artificial shorelines	MT3. Anthropogenic marine shoreline	MT3.a Developed marine shoreline	MT3.a1 Developed marine shoreline	25. Cleared, non-native vegetation, building	98. Cleared, non-native vegetation, building
Plantation	-	T: Terrestrial	T7 Intensive land-use	T7.3 Plantation	T7. Intensive land-use	T7.a Agricultural land	T7.a3 Plantation	25. Cleared, non-native vegetation, building	98. Cleared, non-native vegetation, building

Tiwi Island ecosystem types from this research	Words in Tiwi language	Northern Territory vegetation map (Wilson *et al.*, 1990) Described	 Mapped	Northern Territory Macrogroups (Lewis *et al.*, In prep)	Generalised vegetation types of the Tiwi Islands (Brocklehurst and Edmeades, 1998)	Tiwi Island vegetation types (Woinarski *et al.*, 2000) Described	 Mapped (if different)
Scale of relevancy							
Regional (Tiwi Islands)	Regional (Tiwi Islands)	State (Northern Territory)		State (Northern Territory)	Regional (Tiwi Islands)	Regional (Tiwi Islands)	
Attributes used to define the classes							
Structure and processes		Floristic and structural attributes using a modified Specht (1981) system		Floristics	Floristic and structural attributes using Specht (1970)	Structure and dominant genera	
Ecosystem descriptions							
Eucalypt open forest savanna	*Warta*	3. *Eucalyptus miniata* (Darwin woolly butt), *E. tetrodonta* (stringybark) & *Corymbia nesophila* (Melville Island bloodwood) open-forest with *Sorghum* grassland understorey	3. *Eucalyptus miniata* (Darwin woolly butt), *E. tetrodonta* (stringybark) & *Corymbia nesophila* (Melville Island bloodwood) open-forest with *Sorghum* grassland understorey	4. Australian Darwin Stringybark *Eucalyptus tetrodonta* acleromorphic woodland (M530; Muldavin et al. 2021)	1a: *Eucalyptus miniata* (Darwin woolly butt), *E. tetrodonta* (stringybark) & *Corymbia nesophila* (Melville Island bloodwood) open-forest with *Chrysopogon fallax* (golden beard grass) grassland understorey	Eucalypt forest dense Eucalypt forest mid-open	Eucalypt forest mid-open Eucalypt forest open
		4. *Eucalyptus miniata* (Darwin woolly butt), *E. tetrodonta* (stringybark) open-forest with Sorghum grassland understorey			1b: *Eucalyptus miniata* & *E. tetrodonta* open forest/woodland with tussock grassland understorey	Eucalypt forest open	
		11. *Eucalyptus miniata (*Darwin woolly butt) woodland with grassland understorey			1e: *Eucalyptus miniata* with *Eriachne triseta* tussock grassland understorey		
		7. *E. tetrodonta* (stringybark), *Callitris intratropica* (Cypress pine) woodland with grassland understorey			1i: *Callitris intratropica* open-forest/woodlands with mixed eucalyptus species		
		5. *E. miniata* (Darwin woolly butt), *C. nesophila* (Melville Island bloodwood), *Callitris intratropica* (Cypress pine) open-forest with open-shrubland understorey					
Eucalypt and mixed species savanna	*Warta*	9. *E. tetrodonta* (Stringybark), *E. miniata* (Darwin woolly butt), *C. blesseri* (Smooth-stemmed bloodwood) woodland with *Sorghum* grassland understorey	18. *Corymbia papuana* (Ghost gum), *C. polycarpa* (Long-fruited bloodwood) woodland with grassland understorey	6. Australian Broad-leaved Bloodwood *Corymbia foelscheana* scleromorphic woodland	1c: *Corymbia bleeseri* & *Eucalyptus tetrodonta* open forest/woodland with tussock grassland understorey	Eucalypt woodland	
		18. *Corymbia papuana* (Ghost gum), *C. polycarpa* (Long-fruited bloodwood) woodland with grassland understorey			1d: *Lophostemon lactifluus*, *C. nesophila* & *C. ptychocarpa*, open forest/woodland with tussock grassland understorey		
					1f: *C. polycarpa* open-forest with open-grassland understorey		
					1g: *E. oligantha*, *Erythrophleum chlorostachys* open forest/woodland with *Chrysopogon fallax* tussock grassland understorey		
Treeless plains	*Muriyini*	47. *Acacia* open-shrubland with *Sorghum* grassland understorey	47. *Acacia* open-shrubland with Sorghum grassland understorey	3. Australian Paperbark *Melaleuca viridiflora*–Long-fruited Bloodwood *Corymbia polycarpa* forest and woodland - (e.g. species *M. viridiflora*, *Grevillea pteridifolia*, *C. polycarpa*, *Lophostemon lactifluus*, *M. nervosa*)	5: Sparsely wooded plains	Treeless plains	
					5a: *Acacia* open-shrub land		
					5b: *Grevillea pteridifolia* low woodland		
					5c: *L. lactifluus* low woodland		
					5d: *Acacia* shrub land		
					5e: *Banksia* low woodland		
					1h: *Grevillea pteridifolia* low open-woodland/tall shrubland with *Eriachne burkitti* grassland understorey		
Wet monsoonal rainforests	*Yawurlama* (jungle) *Makaringa* (freshwater stream)	1. Mixed species closed-forest (Monsoon vine thicket)	-	-	4: Monsoon vine-forests	Wet rainforest	
					4b: 'Wet' monsoon forests		
				1. Australasian & East Malesian dry forest	4: Monsoon vine-forests	Dry rainforest	

Dry rainforest and vine thickets	*Yawurlama* (jungle)	1. Mixed species closed-forest (Monsoon vine thicket)	1. Mixed species closed-forest (Monsoon vine thicket)		4a: Dry monsoon vine thickets	
Melaleuca savanna	*Punkaringa* (paperbark) *Pikaringini* (paperbark)	9. *Melaleuca* forest and woodland	15. Melaleuca open forest and woodland	3. Australian Paperbark *Melaleuca viridiflora*–Long-fruited Bloodwood *Corymbia polycarpa* forest and woodland - (e.g. species *M. viridiflora, Grevillea pteridifolia, C. polycarpa, Lophostemon lactifluus, M. nervosa*)	2: *Melaleuca* forests 2b1: M. *viridiflora* woodland/low woodland with *Eriachne burkitti* open-grassland understorey 2b2: *M. viridiflora* and *M. nervosa* low open-woodland with tussock grassland understorey	*Melaleuca* woodland
Grasslands and sedgeland swamp	*Turringiya*	54. Mixed closed-grassland/sedgeland (Seasonal floodplain)	-	14. Northern Australia Tropical Swamp Grass *Pseudoraphis spinescens* –water chestnut *Eleocharis dulcis* –Water Lily *Nymphaea violacea* grassland and sedgeland	6: Swamps/sedgeland	Sedge/grassland
Mangroves	*Mirriparinga* *Pamparinga*	105. Mangal low closed-forest (Mangroves)	105. Mangal low closed-forest (Mangroves)	2. West Pacific (East Melanesia, Micronesia, Polynesia) mangrove (M208)	3: Mangroves 3a: *Sonneratia alba* open-forest/woodland 3b: *Rhizophora stvlosa* closed forest/low closed-forest 3c: *Bruguiera parviflora* closed forest 3d: *R. stylosa, Diospyros ferrea* and *Xylocarpus mekongensis* open-forest 3e: *R. stylosa* and *R. apiculata* open-forest 3f: *Ceriops tagal* var. *australis* closed-forest 3g: *S. caseolaris* and *Lummitzera racemosa* woodland to low open-forest	Mangal forest
Coastal saltmarsh	*Yarti*	106. Saline tidal flats with scattered chenopod low shrubland (Samphire) 111. *Tecticornia* (Samphire) low open-shrubland fringing bare salt pans	106. Saline tidal flats with scattered chenopod low shrubland (Samphire)	-	8: Samphire/Saline coastal flat	Sand and salt flats
Sand dunes	*Kurlimipiti* *Pungamparna*	102. Coastal dune complex	-	-	7: Beaches/chenier ridges/grasslands 7a: Low *Corymbia foelscheana* open-forest 7b: Low *Acacia difficilis* & *Terminalia ferdinandiana* open-woodland 7c: Low *T. ferdinandiana* open-forest	-
Sandy beaches and shorelines	*Tingata* *Wurrungalama* *Yartila* *Kuluwunila* (beach when dry)	-	-	-	-	-
Rocky shorelines	-	-	-	-	-	-
Ocean	*Winga* (ocean) *Juwurti* (deep water)	-	-	-	-	-
Freshwater and brackish rivers, streams, and waterfalls	*Yirringarni* (waterhole, lake, lagoon) *Kilinjini* (waterhole, lake, billabong, swamp)	-	-	-	-	-
Urban and modified	-	-	-	-	-	Built
Plantation	-	-	-	-	9: Plantation	Plantation

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