Northern Australia Environmental Resources Hub

National Environmental Science Programme

Mapping to underpin management of tropical littoral rainforest

Final Report

Helen T Murphy, Andrew Ford, Erin Graham and Dan Metcalfe

CSIRO

JAMES COOK UNIVERSITY AUSTRALIA

This report should be cited as:
Murphy H T, Ford A, Graham E, Metcalfe D (2016) *Mapping to underpin management of tropical littoral rainforest.* CSIRO, Cairns.

Cover photographs
Front cover: Littoral rainforest on Snapper Island (photo Andrew Ford).
Back cover: Littoral rainforest survey (photo Helen Murphy).

This report is available for download from the NESP Northern Australia Environmental Resources Hub: www.nespnorthern.edu.au

The Hub is part of the Australian Government's National Environmental Science Programme. The NESP NAER Hub is hosted by Charles Darwin University.

ISBN 978-1-925167-70-2

October 2016

Printed by Uniprint

Contents

List of Tables

List of figures

Acronyms

ARI ....Annual Recurrence Interval
CSIRO ....Commonweath Scientific and Industrial Research Organisation
DEM...............Digital Elevation Models
DEHWA ....Department of Environment, Heritage, Water and the Arts
DSITIA...........Department of Science, Information Technology, Innovation and the Arts
EAC ....Expert Advisory Committee
EPBC.............Environment Protection and Biodviersity Conservation
GIS ....Geographic Information System
GPS ....Global Positioning System
LGA ....Local Government Area
LiDAR............Light Detection and Ranging
LRF................Littoral Rainforest & Coastal Vine Thickets of Eastern Australia
MHWS ....Mean High Water at Spring Tide
NAER ....Northern Australia Environmental Resources
NCA...............Queensland Nature Conservation Act 1992
DSITIA...........Department of Science, Information Technology, Innovation and the Arts
NESP.............National Environmental Science Programme
RE..................Regional Ecosystems
REDD ....Regional Ecosystem Description Database
RF..................Rainforest
SL ....Sea-level
SPRAT ....Species Profile and Threats Database
TMST.............Theoretical Maximum Storm Tide

Abbreviations

e.g. ....for example
i.e...................for example
km ....kilometres
m ....metres
yr ....year

Acknowledgements

An Expert Advisory Committee was formed for this project and included:

Ashley Leedman, Milena Rafic and Debbie Rudd – Department of the Environment

Tony O'Malley - Terrain NRM

Steve Goosem and Bruce Jennison - Wet Tropics Management Authority

Travis Sydes – FNQ Regional Organisation of Councils

Bridget Armstrong - Queensland Parks and Wildlife Services – Marine Parks

Chris Roach – Queensland Parks and Wildlife Services

Eda Addicott and Mark Newton – Australian Tropical Herbarium

We greatly appreciate the advice of all members who attended several meetings throughout the project, reviewed results and contributed to the report. Thanks in particular to Debbie Rudd, Travis Sydes and Tony O'Malley who provided a thorough review of the final report.

We also benefitted from the expert botanical expertise of:

John Neldner – Queensland Herbarium

Peter Stanton - Exceptional Botanist

Bruce Wannan – Queensland Department of Environment and Heritage Protection

We were very fortunate to visit some otherwise inaccessible Littoral rainforest on a number of Island National Parks thanks to the crew and rangers of the Queensland Parks and Wildlife Services - Marine Parks.

Executive Summary

The aim of the project was to produce fine-resolution mapping of the location of the critically endangered *Littoral Rainforest & Coastal Vine Thickets of Eastern Australia* ecological community (LRF) between Townsville and Cooktown and the threats to its persistence and condition from the impacts of sea-level rise, storm surge and extreme weather events.

A pilot study conducted in the Mission Beach area (Metcalfe *et al.* 2014) developed a mapping approach which accounts for the identification and distribution of Littoral rainforest consistent with the Listing Advice. This project extended that approach across the distribution of the ecological community from Townville to Cooktown.

This project used coastal LiDAR data (1 m grid, 0.15 m accuracy) to compile fine-scale terrain layers to derive inundation levels for an 80 cm sea-level rise and for eight storm surge Annual Recurrence Intervals (ARIs) between 20 and 10,000 years. Spatial layers of the location of LRF and inundation were overlaid to determine the probability and magnitude of risk to the ecological community from these effects and to prioritise management interventions.

The following spatial layers were derived and are available at the CSIRO data portal:

- LRF vegetation that ‘wholly-equates’ to the EPBC Listing Advice
- ‘Potential’ LRF delineating areas consistent with broad characteristics of the community described in the EPBC Listing Advice
- Inundation statistics for each patch of wholly-equate LRF and potential LRF (patches defined by RE mapping) indicating:
    - the proportion of each patch inundated with 80 cm sea-level rise
    - the proportion of each patch inundated at each of 8 ARIs with and without sea-level rise
    - the ARI at which a patch first becomes inundated
    - the ARI at which a patch is >20% inundated
    - the ARI at which a patch is >50% inundated

We describe the distribution and extent of LRF in the study region, the current pressures on LRF in the region and the distribution of LRF in the region with respect to the conservation estate and other tenures.

Our mapping and inundation analysis can be used to define a number of different roles of LRF in the landscape on which a portfolio of management approaches can be derived which allow for the short-, medium- and long-term effects of sea-level rise and storm surge. We define ‘refugial’, ‘buffer’ and ‘leading-edge’ LRF patches by the relative frequency at which they become inundated and suggest management actions to improve resilience of the community as a whole.

1. Introduction

The *Environment Protection and Biodiversity Conservation Act* 1999 (EPBC Act) listed 'Critically Endangered' *Littoral Rainforest and Coastal Vine Thickets of Eastern Australia* ecological community (henceforth Littoral rainforest or LRF) represent a complex of rainforests and coastal vine thickets developed on coastally-influenced substrates (DEHWA 2009). Coastal processes such as salt spray, tidal inundation and storm tides, on-shore winds and unstable and dynamic maritime substrates derive this distinct ecological community. Nationally, Littoral rainforest is highly fragmented and subject to ongoing development pressure as well as other threats such as weed invasion and impacts from feral animals. Additionally, in the Wet Tropics bioregion, it is very susceptible to severe storms and intense cyclones. The north east coast of Australia has seen the passage of two Severe Cyclones (Category 4-5) in the past 9 years (Cyclone Larry in 2006 and Cyclone Yasi in 2011) as well as a number of smaller cyclones. A range of different impacts to LRF and coastal infrastructure are observed following cyclones.

Littoral rainforest occurs at the interface between terrestrial and marine systems, where it provides many ecosystem services; it protects coastal settlements, infrastructure and production systems from erosion, filters sediments, nutrients and pollutants, and provides supporting habitat for biodiversity including EPBC and keystone species such as the cassowary. Furthermore, there is a substantial body of literature highlighting the value of natural coastal vegetation in disaster risk reduction, particularly in wave attenuation and mitigating the effects of cyclonic winds, storm-surge and inundation associated with severe storms (Barbier *et al.* 2008; Shepard *et al.* 2011; Spalding *et al.* 2014). These values can be considered *climate adaptation services* (Lavorel *et al.* 2015); they provide benefits to people, enhance social ability to adapt to climate change, and will become increasingly important in moderating the effects of climate change. Littoral rainforest also provides a welcoming and unique natural environment at the interface between the sea and land in the Wet Tropics, intrinsic to the lifestyle of local communities, and valuable for visitors to experience. The Douglas Shire Council goes so far as to acknowledge this in their welcoming address to the region with the slogan 'Where the Rainforest Meets the Reef'.

The EPBC Act Listing Advice (available at https://www.environment.gov.au/cgi-bin/sprat/public/publicshowcommunity.pl?id=76&status=Critically+Endangered) for Littoral rainforest describes the broad characteristics of the community. However, there is considerable variation in floristic composition and structure across communities and previous work (Metcalfe *et al.* 2014) has shown that the extent of Littoral rainforest in the Wet Tropics bioregion may be greater than the areas currently identified in the national extent section of the Listing Advice. This means that more of this critically endangered resource exists, but also means that those areas that have been misidentified are at risk of further loss.

Given its littoral location, there is also a pressing need to assess the existing and future threats to Littoral rainforest from extreme weather events and sea-level rise in order to prioritise areas for management intervention to maximize its capacity to continue providing the many services that benefit communities and biota in this region.

1.1 Regional Ecosystems and the EPBC Listing Advice

In Queensland, vegetation communities are described using the Regional Ecosystem (RE) framework developed by the Queensland Herbarium (https://www.qld.gov.au/environment/plants-animals/plants/ecosystems/framework/). Each RE is given a three part code e.g. 7.3.2. The first part refers to the bioregion; 7 is the code for the Wet Tropics, Cape York Peninsula to the north is 3 and the Brigalow Belt bioregion to the south is 11. The second part of the code is for the land zone which reflects a simplified geology/substrate landform classification. The relevant land zones for this study are land zone 2 which is Quarternary coastal sand deposits, 11 – metamorphic rocks, and 12 – Mezozoic to Proterozoic igneous rocks. The third part is the ecosystem number and denotes different vegetation. A range of vegetation types are described as rainforest or as having rainforest components.

The key attribute of a community for inclusion on the list is that it is of rainforest vegetation type and occurs in the presence of littoral or maritime processes. The Listing Advice allows for LRF to occur up to (typically) two kilometres from the coast or estuary. Other diagnostic features outlined in the Listing Advice are:

Regional Ecosystems that ‘equate wholly’. The National Context section of the Listing Advice identifies a number of Regional Ecosystems (REs) that occur in the study region that ‘equate wholly’ to the ecological community (Table 1).

Condition Thresholds. The Condition Thresholds section of the Listing Advice notes that the following diagnostic characteristics and condition thresholds should be met:

- Minimum size of a patch to be 0.1 ha; AND
- The cover of transformer weeds (identified in Attachment A to the Listing Advice) is 70% or less; AND
- The patch must have:
    - at least 25% of the native plant species diversity characteristic of the community (Attachment A of the Listing Advice); OR
    - at least 30% canopy cover of one rainforest canopy (tree or shrub) species (Attachment A in the Listing Advice).

Table 1. Regional Ecosystems (REs) which equate wholly to LRF in the study region between Cape Bedford (north of Cooktown) and Rollingstone including their descriptions (Queensland Herbarium 2015).

**RE 11.2.3 occurs in the Brigalow Belt North Bioregion, immediately south of the Wet Tropics Bioregion.*

RE	Description
3.2.1a-b	Evergreen to semi-evergreen notophyll vine forest dominated by *Syzygium forte* subsp. *forte*, *Terminalia muelleri* (Australian almond), *Mimusops elengi* (tanjong) and *Buchanania arborescens* (satinwood). There is a mid-dense to dense uneven canopy and a sparse to mid-dense shrub/low tree layer is usually present. Occurs on coastal dunes and beach ridges in dunefields.
3.2.12	The dense to mid-dense canopy (6-20m tall) is dominated by a variety of species including *Asteromyrtus angustifolia*, *Neofabricia myrtifolia* (yellow teatree), *Syzygium banksii* (Bamaga satinash), *Acacia crassicarpa* (spoon tree) and *Araucaria cunninghamii* (Hoop pine). A sparse emergent tree layer of *A. cunninghamii* (15-30m tall) is present in small patches, generally on the deepest soils on the dune crests. The sparse to mid-dense sub-canopy (2-8m tall) is composed of a variety of trees, with *Atractocarpus sessilis*, *Choriceras tricorne*, *Psydrax* sp., *Leucopogon yorkensis* and *Pandanus conicus* occurring at the highest densities. The sparse shrub layer (0.5-2m tall) is composed of shrubs and young trees of species of the upper layers. *Eugenia reinwardtiana*, *Pimelea aquilonia*, *Myrsine variabilis*, *Choriceras tricorne* and *Leucopogon ruscifolius* occur in large numbers. The ground layer is very sparse, and mainly composed of the graminoids, *Arthrostylis aphylla*, *Lomandra* spp. and *Dianella* spp. Occurs on coastal dunefields and beach ridges.
3.2.13	*Syzygium suborbiculare* (lady apple), *Terminalia muelleri* (Mueller's damson), *Cupaniopsis anacardioides* (beach tamarind) and *Acacia* spp. (wattles) dominate the dense uneven canopy (6-15m tall). *Canarium australianum* (scrub turpentine) and *Gyrocarpus americanus* (helicopter tree) emerge above the canopy at a few sites. *Eugenia reinwardtiana* (sweet cherry), *Tabernaemontana orientalis*, *Mallotus nesophilus* (yellow ball flower) and *Diospyros maritima* (broad-leaved ebony) may form a sparse to mid-dense sub-canopy layer (2-6m tall). A variable shrub layer (0.5-2m tall) is usually present with *Exocarpos latifolius* (broad-leaved cherry), *Ficus opposita* (sandpaper fig), *Alyxia spicata* (chain fruit) and the vine *Abrus precatorius* (gidee gidee) frequently occurring. The ground layer is very sparse to dense in patches and composed of a variable mix of herb species. *Bulbostylis barbata* (a sedge), *Panicum trichoides* (a native panic), *Cyperus pedunculatus* and *C. zollingeri*. Restricted to beach ridges.
7.2.1a-i	Mesophyll vine forest. Beach ridges and sand plains of beach origin, mainly in small patches in the lee of coastal beach ridges in very high rainfall areas.
7.2.2a-h	Notophyll to microphyll vine forest. Species commonly include Cupaniopsis anacardioides, Diospyros geminata, Canarium australianum, Alphitonia excelsa, Acacia crassicarpa, A. mangium, Hibiscus tiliaceus, Pleiogynium timorense, Chionanthus ramiflorus, Blepharocarya involucrigera, Mimusops elengi, Polyalthia nitidissima, Millettia pinnata, Geijera salicifolia, Ficus opposita, Sersalisia sericea, Terminalia muelleri, T. arenicola, Drypetes deplanchei and Exocarpos latifolius. Beach ridges and sand plains of beach origin.
7.2.5a	Mesophyll to notophyll vine forest of *Syzygium forte* subsp. *forte* (white apple). Beach ridges and sand plains of beach origin.
7.2.6b	Evergreen notophyll vine thicket with Acacia crassicarpa, Elaeodendron melanocarpum, Aglaia elaeagnoidea and Drypetes deplanchei. Aeolian dunes.

RE	Description
7.11.3b	*Terminalia arenicola* and *Acacia polystachya* low closed forest. Coastal metamorphic headlands.
7.12.11d	Low notophyll vine forest and thicket. Exposed rocky coastal headlands.
*11.2.3	Microphyll/notophyll vineforest to semi-deciduous vine thicket on Quaternary coastal dunes. Commonly consists of several of the following trees: *Pleiogynium timorense, Mimusops elengi, Cupaniopsis anacardioides, Exocarpos latifolius, Sersalisia sericea* and *Diospyros geminata*. In dry, exposed and windswept locations, this RE may only reach 4-5 m, and include deciduous emergent species such as *Gyrocarpus americanus* and *Brachychiton australis*. At its best development this formation grows to 15 m and includes further species such as *Ficus virens, Aglaia brownii, Polyalthia nitidissima, Canarium australianum, Miliusa brahei* and *Ficus* spp. A shrub layer may be present with *Carissa ovata, Capparis sepiaria, Eugenia reinwardtiana, Drypetes deplanchei* and *Aidia racemosa*. Vines are common, including *Sarcostemma viminale* subsp. *australe, Jasminum didymum, J. simplicifolium, Abrus precatorius* and *Cissus* spp. A ground layer is sparse or absent. Occurs on Quaternary coastal dunes and adjacent swales. Best developed on secondary dune swales and areas protected from strong winds. Soils are fine to coarse beach sands possibly enriched by calcareous sediments.

1.2 This Project

A recent pilot study conducted in the Mission Beach area (Metcalfe *et al.* 2014) developed an improved mapping approach which accounts for the identification and distribution of Littoral rainforest while remaining consistent with the EPBC Act Listing Advice. The Mission Beach pilot study described the following rules to delineate the location of potential LRF in that study region:

1. REs that equate wholly according to the Listing Advice.
2. Rainforest <75 m from mean high water at spring tide (MHWS) on an open coast, excluding areas >10 m above sea-level on basalt-derived soils.
3. Rainforest on coastal sand deposits <2km from an open coast that have not been obviously reworked by fluvial processes.
4. Rainforest in high or medium hazard storm tide inundation areas <200m from open coast
5. Wetlands and waterways are excluded.
6. Other identified Littoral rainforest sites, based on ground-truthed expert advice.

The Mission Beach Pilot Study also noted that the rules would ideally be tested and refined for climatic subregions within the broader bioregion. This project extends the approach taken for Mission Beach, allowing for locally-specific modification of the above rules across the distribution of the LRF community from Townsville to Cooktown.

2. Methods

The mapping methodology involved an iterative GIS and field ground-truthing process.

2.1 Fieldwork methodology

Before any fieldwork was undertaken, coastal vegetation types of interest were compiled throughout the study area using a variety of sources and methods. The aim of the fieldwork was to document presence and absence of wholly compliant or otherwise REs for a particular polygon, using the current Queensland Herbarium Regional Ecosystem GIS shapefile as a starting point. The RE shapefile along with high resolution aerial photography provided for a visual desktop assessment of vegetation structure and foliage cover from which sites were selected for ground-truthing. Actual sites targeted for field assessments were from a variety of sources, including:

1. Polygons mapped as wholly compliant with the Listing Advice
2. Polygons not mapped as wholly compliant, but adjacent to wholly compliant polygons, irrespective of substrate
3. Polygons mapped as non-compliant but from aerial photography interpretation appeared to be a closed forest ecosystem on sand or rocky headlands
4. Unmapped areas which appeared to harbour compliant vegetation from aerial photography and/or expert opinion
5. Areas accessed en-route to targeted sites which are in any form of the above

Once a site was reached a series of assessments and observations were recorded. The assessments conducted were designed to be relatively simple and brief, yet concise and informative. See Appendix A and Appendix B for all site assessments. The actual assessment, excluding extent area, was derived from what was visible from the waypoint assigned to the community during the desktop assessment, which commonly covered about 20 m x 20 m, i.e. 10-15 m in any direction. Each assessment took approximately 20 minutes to complete and consisted of the following information:

1. Site number, site name, date, latitude and longitude (e.g. 025, Oak Beach rd, 5/11/2015, -16.60038, 145.52135)
2. The RE that the waypoint/geocode is mapped as (e.g. 7.2.1i)
3. The RE that the waypoint/geocode is interpreted as from ground-truthing (e.g. 7.3.10a)
4. Presence of any weeds within the assessment area (e.g. *Cocos nucifera*)
5. Condition assessment:
    a. Soil and substrate description (e.g. fine sand, little humus, some pumice and coral debris). Landform description if obvious (e.g. dune slope)
    b. Canopy height. This is the average canopy height which is visible from a number of trees. If emergents were present, their height was also recorded.
    c. Canopy species. Up to six species were recorded where possible. Emergent species were recorded.
    d. Additional species. These species, usually also up to six, were selected from among the understory, ground layer and vine species as indicators of the community composition. Epiphytes were only recorded if present and conspicuous.

e. Impacts. This included anything that was currently impacting, or had left evidence of having impacted the site or general area (e.g. cyclonic winds, storm surge, pigs, vegetation management, camping area, fire, clearing for road construction, walking track, vehicle access, etc.). This also included vegetation where there was clear succession taking place (e.g. advanced rainforest incursion).
f. Queensland Nature Conservation Act (NCA)/EPBC listed plant species present. Unusual or cryptic species of bioregional significance were recorded. Selected voucher specimens were collected, processed and sent to Australian Tropical Herbarium in Cairns (see Appendix C).
g. Presence or absence of littoral processes (e.g. Is the substrate maritime deposited sand? Does exposure to winds shape and/or define the community? Is there evidence of storm tide inundation?)
h. Estimate of the extent or area of the assessed RE community. Usually in the form of a finite area (e.g. 30 m wide and 60 m long) or open-ended (>50 m wide and >100 m long).
i. Aspect and altitude were estimated, either on site where possible or post-assessment with GPS and topographic maps respectively.
j. Strand or other comments (optional). For sites assessed on the landward side of the strand, an indication of the strand vegetation was supplied in the form of a species assemblage (e.g. Strand 12m wide: *Hibiscus, Sophora, Pandanus, Crinum, Calophyllum inophyllum* and *Ischaemum*). Presence (and relative abundance) or absence of *Casuarina equisetifolia* was noted, particularly where the RE mapping was designated as 7.2.7a (e.g. discontinuous line of *Casuarina*). Where sites were clearly surrounded by or adjacent to another conspicuous RE vegetation type, this was clarified (e.g. strip of *Mel. leucadendra* to the west and parallel to beach).
k. LRF determination. Once all considerations and interpretations were completed and based upon field assessment, the site was classified Littoral Rainforest or not.

2.2 Mapping methodology

To map the presence of potential LRF communities, GIS techniques were applied to create shapefiles consistent with Metcalfe *et al.*'s rules as described in the Introduction ('This Project'), with some modification. These rules were assessed and refined using an iterative approach as ground-truthing progressed. Waterways and wetlands were excluded as per Metcalfe *et al.*'s rules. The rationale for the following rules is fully described further below:

Rule 1: Regional Ecosystems that equate wholly with the Listing Advice

Rule 2: Rainforest on basalt, granite, or metamorphic geologies up to 75 m from high water mark on an open coast (i.e. excluding estuaries and wetlands)

Rule 3: Rainforest on coastal sand deposits up to 2 km from an open coast

Rule 4: Other Regional Ecosystems on sand up to 2 km from the coast and the V-rule

Rule 1: Regional Ecosystems that equate wholly with the Listing Advice

For the Wet Tropics the following REs were regarded as wholly compliant: 7.2.1 a-I, 7.2.2 a-h, 7.2.5 a, 7.2.6 b, 7.11.3 b and 7.12.11 d; and for Cape York: 3.2.1 a-b, 3.2.12, 3.2.13, 3.2.28, 3.2.29, 3.2.31, 3.2.11 and 3.12.20 (Table 1). It should be noted that RE 11.2.3, which also equates to Littoral rainforest and occurs in the Brigalow Belt North Bioregion, was listed as a component of the nationally endangered ecological community, *Semi-Evergreen Vine Thickets of the Brigalow Belt (North and South) and Nandewar Bioregions*. As a result of this earlier legislation, RE 11.2.3 is not included as part of the Listing Advice for LRF. The nearest recognised occurrence of this RE to the Wet Tropics bioregion is at Yabulu, immediately south of the Wet Tropics, between Townsville and Rollingstone.

Rule 2: Rainforest on basalt, granite, or metamorphic geologies up to 75 m from high water mark on an open coast

When the combination of a rocky substrate and a closed woody vegetation type occurs in close proximity to the high water mark, the potential for coastal vine-thicket or Littoral rainforest development is greatly enhanced. A wide variety of rainforest types do occur on rocky substrates adjacent to or immediately above the high water mark. However, for acceptance as LRF the vegetation must comply with the Listing Advice description and condition thresholds. The usual expectation for this development would be an exposed coast which faces more or less east to south (90-180 degrees), with the prevailing south-easterly (125-135 degrees) winds being the most common. Adaptation to salt-laden winds in the Wet Tropics is effectively prevented by the calming effect of the Great Barrier Reef (Metcalfe *et al.* 2014). Consideration also needs to be made in regard to local topographic conditions (i.e. coastal hills and peaks), which may create eddies as a result of winds being constantly deflected onto an otherwise unexposed coastline.

The use of a 75 m threshold distance from the high water mark was based upon the relative canopy widths of three trees, which appears to be the limit of littoral influence of exposure to retain a discrete ecological community (Metcalfe *et al.* 2014). Reducing the threshold distance from 2 km to 75 m eliminates other rainforest types that occur close to the high water mark but whose development and floristics are clearly not under littoral influence.

Wholly compliant REs include granite (the "12" within 3.12.20 and 7.12.11d) and metamorphic (the "11" within 7.11.3b) substrates. The inclusion of basalt was based upon the findings of Metcalfe *et. al.* (2014) from the Mission Beach area. Recognising that there is a distinct ecological community of littoral origin on basalt they suggest capping the influence at 10 m asl. There is no currently accepted RE for LRF on a basaltic substrate in the Wet Tropics. This limit for basalt is well deserved as the Mission Beach area is not regarded as a very windy area, unlike latitudes further north and south. Currently there appears to be no upper limit of altitude for rocky forms of Littoral rainforest/thicket. The rationale is quite straight forward, different rates of exposure and intensities of winds occur in different places and habitats. Consultation with the SPRAT lists (DoE 2016) should enable correct LRF recognition.

Cyclones, although being of maritime origin, have the ability to shape the structure and floristics of littoral and non-littoral vegetation, but cannot be included as a determining contributor for development of LRF. Cyclonic winds are multidirectional in both a spatial and temporal timescale. This transiency reduces the ability to form specialised and discrete communities in the strict 2 km limit which is suggested in the Listing Advice. There are however specialised communities on near-coastal hillsides well away from the high water mark that have long been recognised as 'cyclone scrubs' (Webb 1958) and which cannot be considered as Littoral rainforest/thicket.

Rule 3: Rainforest on sand up to 2 km from an open coast

Coastal sand deposits between Rollingstone and Cooktown are predominantly Holocene in age. All rainforest which occurs on these deposits within 2 km of the coast are included under the range of REs in the Listing Advice. Thus no rainforest on sand within the study area was excluded under these circumstances. It should be noted that the deposits, frequently in the form of dunes and low prograding dune/sand plains can extend up to 10 km from an open coast for communities in the Cape York bioregion, especially in the Cape Bedford area north of Cooktown. Dunes which support LRF on Hinchinbrook Island and in the Cooktown area can be in excess of 30 m asl.

Rule 4: Other REs on sand up to 2 km from the coast and the V-rule

Between the combination of the Listing Advice and the indicative SPRAT listed species, the presence of *Melaleuca leucadendra* is permitted, as are emergent *Corymbia/Eucalyptus* above a canopy which must contain at least 30% canopy cover from the above lists. Therefore it is necessary to consider several other REs which occur on coastal sand deposits. These include: 7.2.3, 7.2.6 (excluding 7.2.6b), 7.2.7 (excluding 7.2.7c) and 7.2.8. These REs have the potential to have a well-developed Littoral rainforest/thicket closed canopy with aforementioned species as emergents. Presence of this closed canopy is a result of rainforest invasion and subsequent succession in the absence of recurrent fire. In many sites the sclerophyll component of the RE is now represented by emergent trees only, with the sclerophyllous and fire-tolerant understory fully replaced by rainforest congeners. The source vegetation mapping, from which the RE mapping is largely derived, noted in a field of the attribute table for those REs the letter “v”. In this instance “v” stands for vine-forest, recognising that a well-developed rainforest understory exists.

RE 7.2.8 deserves special mention as it is described as “*Melaleuca leucadendra* (weeping tea tree) open forest to woodland” (Queensland Herbarium, 2015). When this RE becomes heavily invaded by SPRAT Littoral rainforest species, due to either changes in hydrology or fire regimes, the potential for inclusion into LRF is enhanced as *Melaleuca leucadendra* is on the indicative SPRAT list.

The ubiquitous RE 7.2.7a covers a wide and varied number of potential iterations of strand vegetation, which may or may not actually contain the host dominant descriptive species *Casuarina equisetifolia* (coast sheoak). Areas where coast sheoak is absent or restricted to a single and discontinuous line of trees one canopy wide at the strand may be better interpreted as Littoral rainforest, as long as the various conditions and thresholds have been met. In the ‘super-wet zone’ of the Wet Tropics (sensu Metcalfe *et al.* 2014), pure coast sheoak woodland is a very rare ecosystem and is usually very quickly invaded by SPRAT species. Alternatively, coast sheoak woodlands in these areas could also be viewed as the earliest stage of succession from disturbed coastal sand until the final stage of rainforest incursion has occurred. More seasonally dry areas (such as Ingham-Rollingstone and Cooktown) appear to support a better developed and extensive coast sheoak community, with rainforest incursion being minimal in places. However, even in these seemingly ’stable’ areas, 7.2.7a still has the potential to be successionally replaced by Littoral rainforest in the absence of fire or disturbance, such as severe cyclones and storm surges which can temporarily destroy or hold back the invading rainforest.

2.2.1 Species lists

As mentioned above, the relevant SPRAT lists need to be consulted before an accurate assessment of LRF can be made. Metcalfe *et al.* (2014) make the valid point that several critical omissions to the indicative list for the Wet Tropics need to be rectified. Those species that are recommended for inclusion are for example: *Aidia racemosa, Hernandia nymphaeifolia, Erythrina variegata, Pandanus tectorius* and *Terminalia catappa.*

Within Cape York we strongly recommend species such as *Cyclophyllum maritimum, Dillenia alata* and *Psydrax banksii* be included as they are commonly encountered low-growing trees and tall shrubs of Littoral rainforests, especially in the Cooktown area. The SPRAT lists also requires nomenclatural updating, particularly for species that have undergone taxonomic change. For example, *Diospyros hebecarpa*, which is on the Wet Tropics list, has now been split with *Diospyros uvida* now recognised. It is actually *D. uvida* which occurs in Littoral rainforest, from the north of the Daintree River area, and not *D. hebecarpa*.

2.3 Storm-surge and sea-level rise analysis

LiDAR-derived 1m resolution digital elevation models (DEMs) provided from multiple vendors and obtained from the Terrain and NQ Dry Tropics NRM groups were sourced for the coast of Queensland, running near continuously from Cooktown to Townsville (Table 2). Predicted storm surge water level height rasters were downloaded from Queensland's Spatial Catalogue, made available as part of Queensland's Department of Science, Information Technology, Innovation and the Arts (DSITIA) Natural Disaster Resilience Program (NDRP) (GHD Pty. Ltd. 2014). Briefly, GHD used advanced storm surge modelling to predict the statistical return period storm water levels for seven average recurrence intervals (ARI) or return intervals of 20, 50, 100, 200, 500, 1,000, and 10,000 years, as well as the theoretical maximum storm tide (TMST) level for the state. An ARI (or Return Period) is simply the expected average elapsed time in years between equalling or exceeding a specified event level. The probability of experiencing the "n" year ARI event within any consecutive period of "n" years is approximately 64%, i.e. more likely than not. The TMST considers what upper limit of storm surge magnitude might be physically possible through a combination of specifically extreme storm parameters, without regard to their likely joint probability or overall probability of occurrence, and then combines that resulting magnitude with the highest astronomical tide (HAT).

The level of inundation caused by a storm surge is due to a combination of many factors, including extreme winds, the astronomical tide, wave setup, wave run-up, and ocean currents, all of which were considered in GHD's modelling. In addition to storm surge, LRF is likely to be impacted by predicted rises in sea level. A projected sea-level rise of 0.8 metres by the year 2100 is based on climate modelling and probable scenarios of world development presented in the IPCC Fourth Assessment Report. The Queensland Government also uses this sea-level rise for its coastal hazard mapping.

We estimated the inundation areas for sea-level rise by itself, as well as in combination with each of the ARI's. The worst case scenario can be considered as the combined effect of a significant storm surge striking the coast at the HAT with the highest predicted sea level. Due to the difficulty in obtaining HAT values for the entire study area, and given that HAT is included in the estimated TMST modelling, the worst-case scenario in terms of inundation is the TMST.

For each ARI, we subtracted the predicted water levels from the LiDAR-derived DEM to determine which areas along the coast would be inundated, and these areas were then intersected with the LRF patches to determine how much of each patch was inundated.

Table 2. Source of the LiDAR-derived digital elevation models (DEM's) used in the analysis and associated uncertainty (RMSE - root mean square error; Accuracy=1.96*RMSE).

Dataset	Vendor	RMSE	Accuracy
Cooktown_2009_Prj	Photomapping Services	0.086	0.169
Cooktown_2013_Twn	RPS Group	0.103	0.202
Cairns_2010_Rgn	Terranean Mapping Technologies	0.056	0.110
Yarrabah_2009_LGA	Fugro Spatial Solutions Pty Ltd	0.17	0.333
Cassowary_Coast_2009_Ctl	Photomapping Services	0.066	0.129
Cassowary_Coast_2009_Prj	Fugro Spatial Solutions Pty Ltd	0.17	0.333
Hinchinbrook_2009_Ctl	Photomapping Services	0.134	0.263
Hinchinbrook_2009_Prj	Fugro Spatial Solutions Pty Ltd	0.17	0.333
Townsville_2009_Ctl	Photomapping Services	0.079	0.155

3. Results

3.1 Site Assessments

In total 156 sites between Cooktown in the north and Toomulla Beach in the south were assessed for presence or absence of LRF, based upon the thresholds and criteria in the Listing Advice. Of these sites, 65% were assessed in the field as being LRF, whereas 35% were of other vegetation types, ranging from mangrove and lowland rainforest to a variety of woodlands. From these assessments 59 voucher collections were made. The collections represent a variety of circumstances, ranging from disjunctly occurring EPBC/NCA listed species (e.g. *Buchanania mangoides* from Snapper Island and Cow Bay), bioregional endemic EPBC/NCA listed species (e.g. *Gardenia actinocarpa* from Noah Creek area), biogeographical range extensions (e.g. *Litsea breviumbellata* at a new southern limit on Hinchinbrook Island), uncommonly encountered species (e.g. *Gynochthodes sessilis* from Hinchinbrook Island), unusual habitat occurrences (e.g. *Stenochlaena palustris* from Archer Point area, previously not collected in the Cooktown area) and from locations which were difficult to access (e.g. *Guettarda speciosa* from Goold Island). See Appendix C for a complete list of the collections made.

3.2 Mapping

Figure 1 Example of combined Wholly (Rule 1) and Potential LRF (Rules 2, 3, 4)

Spatial layers were created of LRF that 'wholly' equate to REs described in the Listing Advice (Rule 1) and 'potential' LRF which includes REs that are included given the mapping rules (Rule 2, 3 and 4) described in the Methodology (Figure 1). In the following sections, we describe how well the mapping for wholly and potential LRF performed compared to the distribution of the community on the ground.

3.2.1 *Wholly-equate mapping*

Table 3 shows the breakdown of the actual representation and proportion of sites which were assessed in the field as being LRF or not, relative to the wholly-equate RE mapping (i.e. Rule 1). Of the 156 sites assessed, 23 assessments were conducted where no current RE mapping exists. These were predominantly from Snapper and Russell Islands, but also included five sites where the classification in the RE mapping was given as 'Ocean' or 'Disturbed'.

Table 3. Proportion and number of sites ground-truthed for presence/absence of Littoral rainforest versus Regional Ecosystem mapping.

	Regional Ecosystem Mapping – wholly-equate		
Field Assessment	Mapped as LRF	Not mapped as LRF	Unmapped sites
Assessed as LRF (101 sites)	24% (24/101)	65% (66/101)	11% (11/101)
Not assessed as LRF (55 sites)	16% (9/55)	62% (34/55)	22% (12/55)

Sixty-five percent of sites that were assessed as being LRF in the field, were not mapped as a wholly-equate RE, leaving 24% that were mapped as wholly-equate, with the remainder being LRF that was not mapped. The majority of sites that were field-assessed as LRF but not mapped as LRF were originally mapped as 7.2.7a, followed by a variety of other REs including 7.2.3 a-c and 7.2.8.

Of the sites that were not assessed as LRF in the field, 62% were not mapped as wholly-equate LRF, with 16% occurring in sites that were in a wholly-equate RE. Of the sites which were mapped as wholly-equate LRF but the field assessment disagreed, the reasons for this discrepancy were generally related to substrate and vegetation classification. The majority of sites in this category had an alluvial substrate rather than the maritime-derived sandy substrate, and there was no evidence of surface deposition of sand. In all of these instances the floristic composition was also at odds with the SPRAT lists and RE descriptions.

Although not shown in the table, no distinction was made between whether an area was mapped as a particular wholly-equate RE but the ground assessment judged the RE as a different wholly-equate RE. These instances were recorded in the site assessments (Appendix A). An example of this was recorded near Archer Point south of Cooktown (sites 50 and 51 in Appendix A). The RE was mapped as a heterogeneous Cape York polygon of 3.2.1b/3.3.2a, with both maritime sand and alluvium influence. RE 3.2.1b is described in Table 1 above, however the ground assessment revealed an essentially tall monoculture canopy of *Syzygium angophoroides.* This community lies in the swale between two tall dunes and has permanent water present. It is therefore better allocated to the Wet Tropics RE 7.2.1e, which is also a wholly-equate RE. However, because this particular site lies further than 2 km from the coast it was not captured by our mapping.

As noted previously, the RE 7.2.7a (non- wholly-equate RE) was the most problematic RE in terms of field assignment versus mapping scenario. In fact 18 sites were completed in 7.2.7a, with 12 (66%) being assessed as LRF. This anomaly is clearly related to the presence of *Casuarina*, and not necessarily the abundance of it or canopy forming rainforest species. In many sites, a complete canopy existed and was frequently dominated by *Calophyllum inophyllum* (Beach Calophyllum), with *Casuarina* being represented by isolated trees or as a discontinuous single tree depth strip along the strand. The challenge of assessing this RE was further compounded by the successional and dynamic (periodically eroded then redeposited substrate) nature of the *Casuarina* community and accurate assessments could only be made in the field or by using high resolution aerial photography/images.

Interpretation of currently mapped polygons of 7.2.7a in particular, by members of the Queensland Herbarium's mapping unit, suggests that there may be significant changes to the current coastal RE mapping in the Wet Tropics, with these polygons now attaining recognition as LRF. This recognition will see more area mapped as LRF and less mapped as 7.2.7a. Furthermore, it is anticipated that many polygons in the Wet Tropics will become heterogeneous, enabling the EPBC listed component of the polygon to be acknowledged.

At the bottom of Table 1 and noted in the Methodology section above, RE 11.2.3 was included because the nearest occurrence was just south of the Wet Tropics bioregion. This RE is clearly related to 7.2.2a and could be interpreted as a depauperate and more seasonally dry version of it. A site assessment at Toomulla Beach, between Rollingstone and Yabulu, suggested that the floristic composition and structure of the site was better aligned to 11.2.3 rather than 7.2.2a. This inclusion now represents an outlier of the Brigalow Belt North Bioregion, but within the geographic confines of the Wet Tropics bioregion. The Queensland Herbarium is adopting this recognition and it will be reflected in an updated version of RE mapping. As 11.2.3 is not within the wholly compliant RE framework of LRF, it cannot be treated as such. However, this polygon will be captured as an outlier within the EPBC listed *Semi-Evergreen Vine Thickets of the Brigalow Belt (North and South) and Nandewar Bioregions.*

3.2.2 Combined Wholly and Potential LRF mapping

When incorporating Rules 2, 3 and 4 with the wholly-equate (Rule 1) mapping, a much greater proportion of sites assessed as LRF in the field were captured: 67% compared with 24% in the wholly equate layer (Table 4). Twenty-nine per cent of sites that were assessed as LRF in the field were still not captured by the combined mapping.

Table 4 Proportion and number of sites ground-truthed for presence/absence of Littoral rainforest versus wholly or potential LRF mapping.

	Captured in Wholly or Potential mapping		
Field Assessment	Captured as LRF	Not captured as LRF	Unmapped sites
Assessed as LRF (101 sites)	67% (68/101)	29% (22/101)	11% (11/101)
Not assessed as LRF (55 sites)	42% (23/55)	36% (20/55)	29% (12/55)

Nine of the 22 LRF sites not captured by the combined mapping were in the Cape York bioregion. Variation in the protocols and scale used to map REs across Queensland introduces a range of difficulties for appropriately demarcating LRF. For example, the Cape York bioregion is mapped at a much broader scale than the Wet Tropics bioregion, with a minimum polygon size in Cape York of 5 hectares (compared to the Wet Tropics which is 0.5 hectares) and a minimum width of 75 m mapped at 1: 100,000. This has the potential to create discrepancies, irrespective of the actual mapping polygon units. In addition, for an RE to be included in a heterogeneous polygon, it must constitute a minimum of 5% of the total polygon area (i.e. at least 0.25 ha). Therefore relatively small beach-fronts, minor dunes and rocky shores where LRF occurs have been excluded from the RE mapping. The Listing Advice states that the minimum size for recognition of a patch of LRF is 0.1 hectares. This issue of heterogeneous polygons not adequately capturing LRF also occurs in the Wet Tropics bioregion, accounting for a further eight sites in this category.

In addition to nine sites not captured due to mapping issues, two sites we surveyed and assessed as LRF in the field were not deemed as LRF with the currect rules because they lie further than 2 km from the coast. The Listing Advice allows for LRF to occur (typically) up to 2 km from the coast or an estuary; however for communities in the Cape York bioregion this is inadequate, with recognisable LRF occurring up to 10 km from the coast, especially in the Cape Bedford area north of Cooktown.

Seven sites were excluded from mapping due to errors in the current RE mapping. One site was mapped as non-remnant vegetation, however, the field survey and interpretation of satellite imagery clearly shows LRF. The area adjacent to this site had recently been cleared for residential development (see Figure 6). Five sites in the Yorkeys Knob area were mapped as ‘Ocean’ or non-remnant where there was clearly vegetation. Anecdotal evidence suggests the Yorkey Knob beach area has accreted significantly over the past 30 years and the RE mapping does not yet reflect the occurrence of LRF and other vegetation where previously there was none.

Of the sites not assessed as LRF in the field, 42% are captured by the combined mapping. Several of these represent RE mapping errors which can be remedied. The remainder are sites captured under the rule that allows for rainforest on sand within 2 km of the coast but where other diagnostic characteristics were not met. For example, the presence or density of characteristic species was not consistent with the Listing Advice, or littoral processes were absent.

3.3 Extent of Wholly and Potential LRF

The total area of LRF mapped as wholly equating to the Listing Advice in the study area was 1,875 hectares with a further 13,276 hectares mapped as potential LRF. Across the study area, the largest proportion of wholly and potential LRF was contained within the Cassowary Coast Local Government Area (LGA) (Figure 2). It should be noted that the study area encompassed only a small proportion of the Cook, Townsville and Hope Vale LGAs, but included the entirety of Douglas, Cairns, Yarrabah, Cassowary Coast, Palm Island and Hinchinbrook.

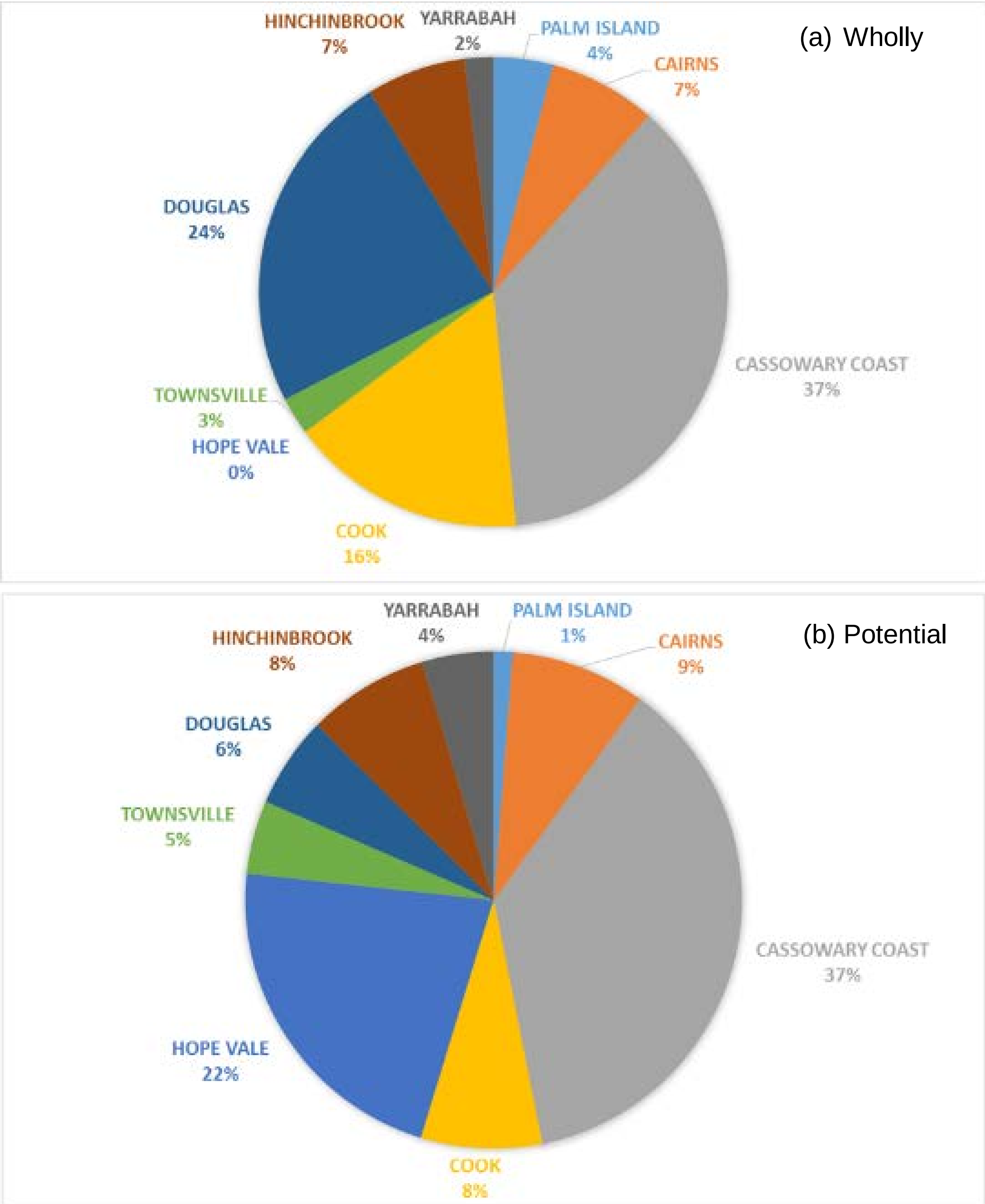


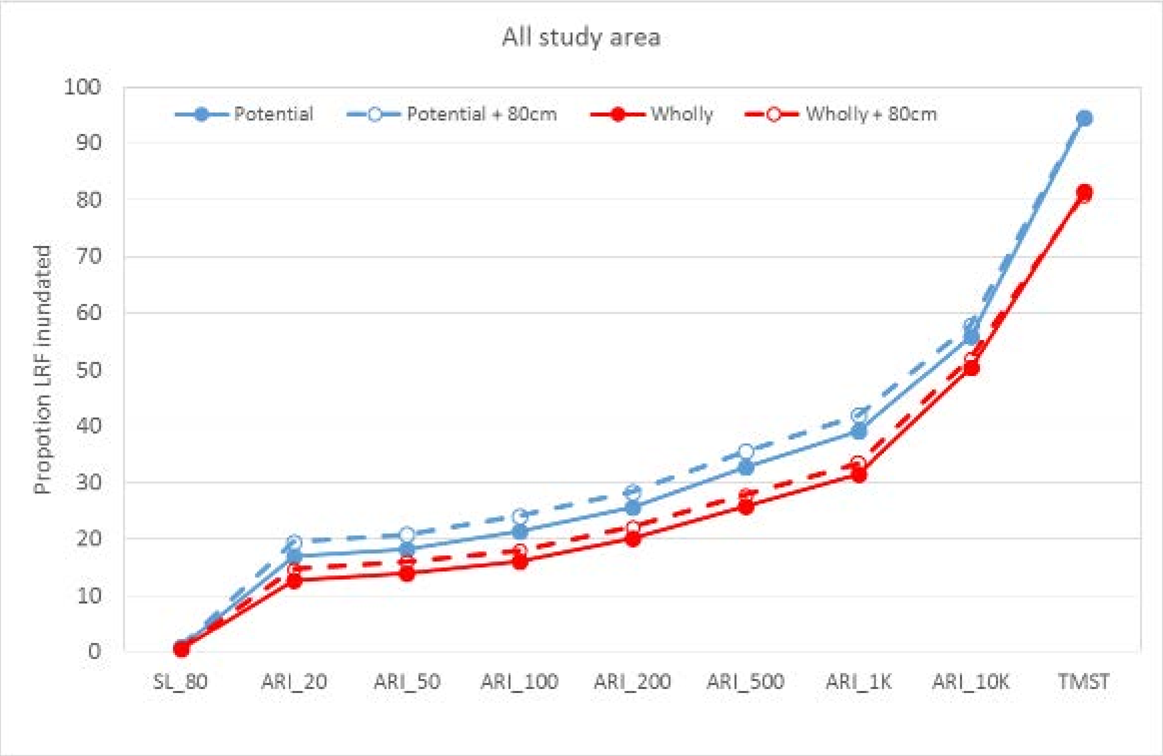
Figure 2 Distribution of (a) wholly and (b) potential LRF in LGAs across the study area.

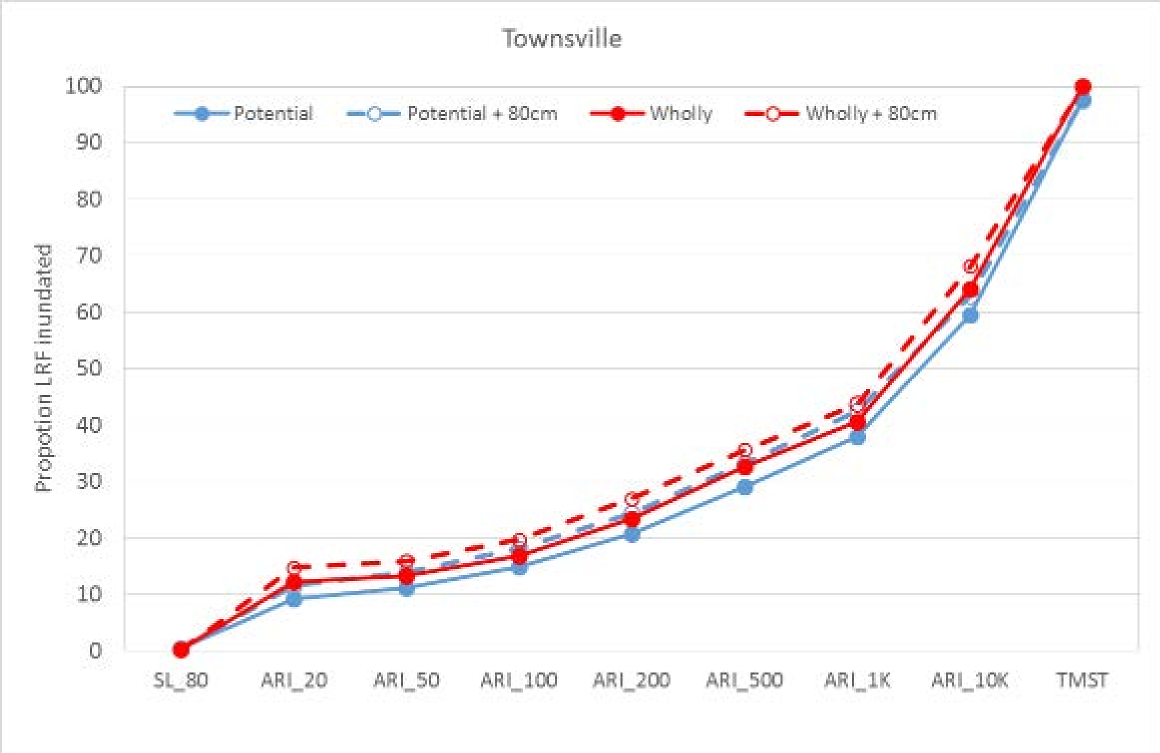
3.4 Storm Surge and Sea Level Rise Impacts

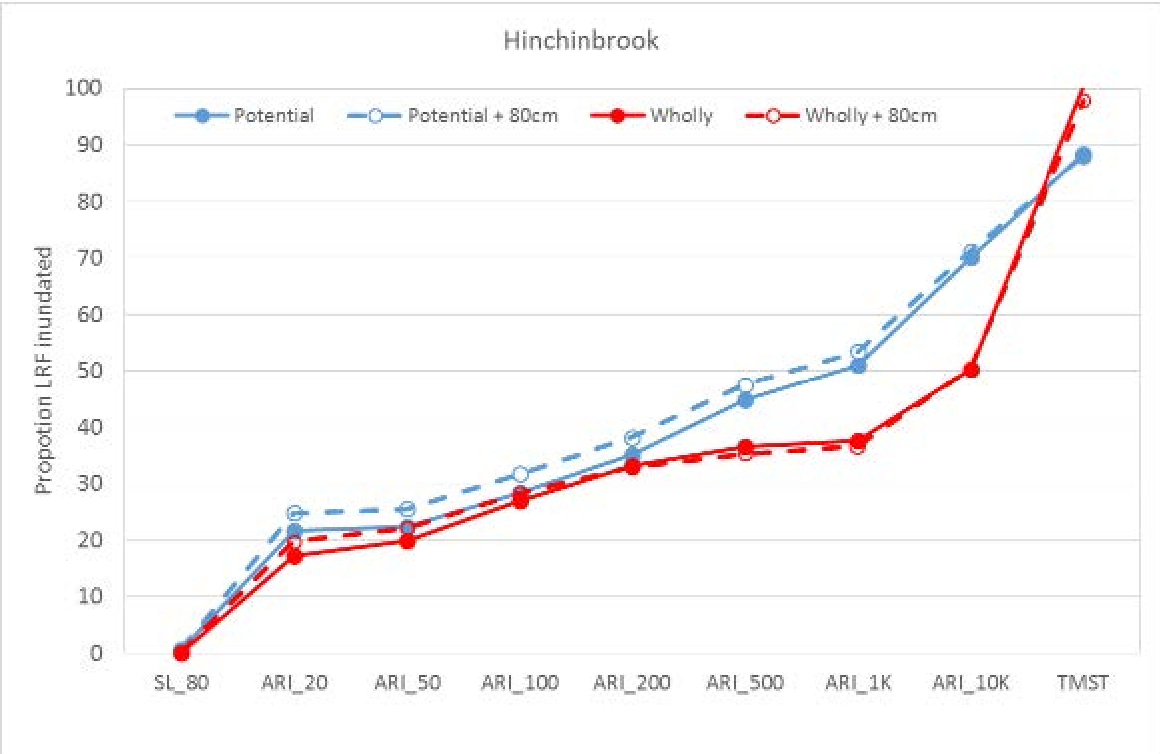
Over the entire study area a sea-level rise of 80 cm had only a minor effect on LRF, inundating less than 1% of wholly-equate and potential LRF (Figure 3). The highest proportion of LRF inundated by sea-level rise occured in the Cairns LGA (3.2% of wholly and 1.4% of potential) and in Yarrabah (2% of wholly).

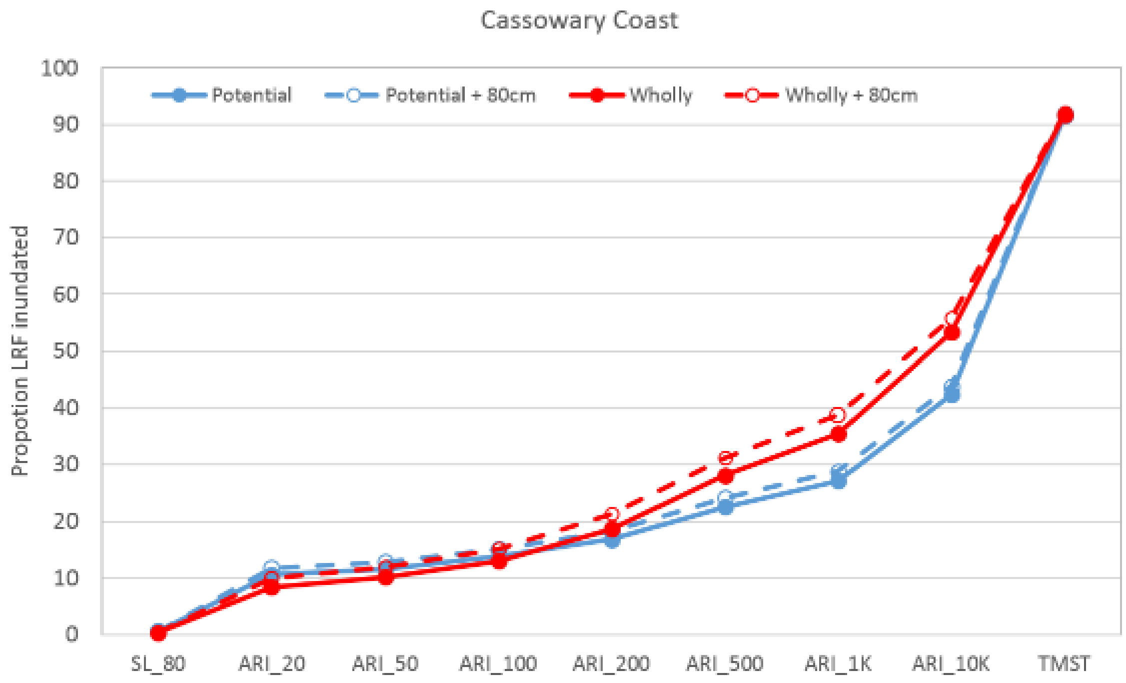
Even relatively regular events (20 yr ARI) inundated significantly more LRF with 12% of wholly and 17% of potential LRF being inundated across the study area without sea-level rise and 15% of wholly and 19% of potential LRF being inundated when combining an 80 cm sea-level rise scenario with a 20 year ARI. The area of inundation increased, as expected, with more severe events; over 50% of wholly-equate and 55% of potential LRF would be inundated in a 10,000 yr ARI across the study area. Under the Theoretical Maximum Storm Tide, 81% of wholly LRF would be inundated and 95% of potential LRF.

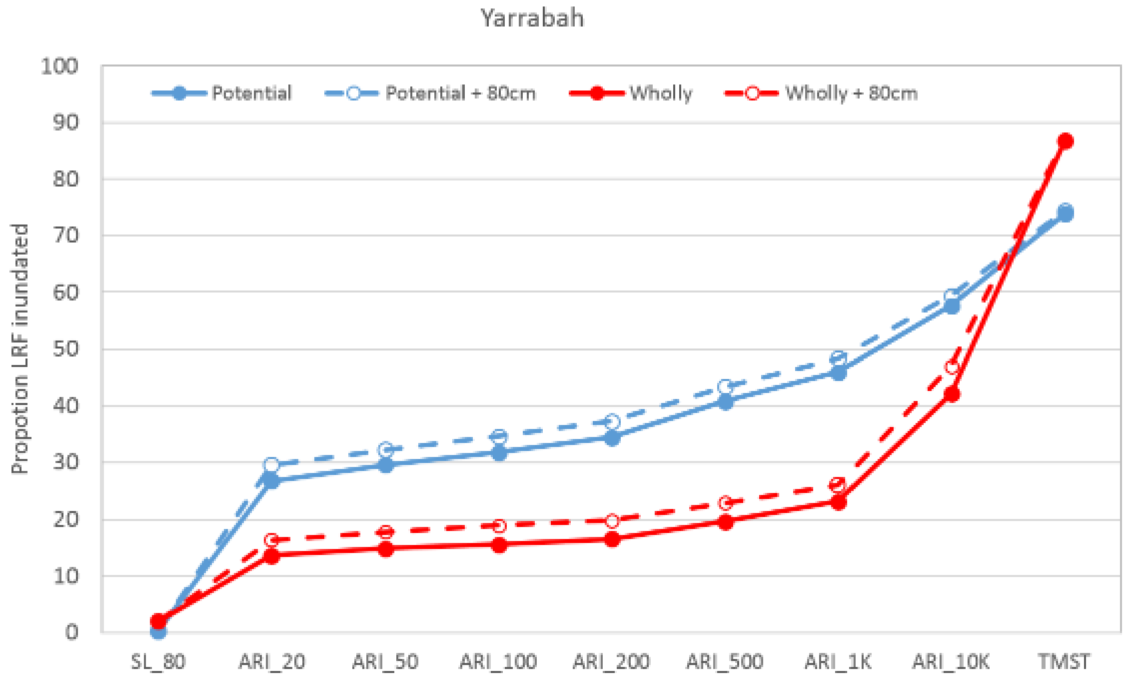
The highest levels of inundation at low return intervals occured in the Cairns region where approximately 30% of wholly-equate LRF becomes inundated (at 20 yr ARI). Nearly 30% of potential LRF becomes inundated in Douglas and Yarrabah LGA at the 20 yr ARI.

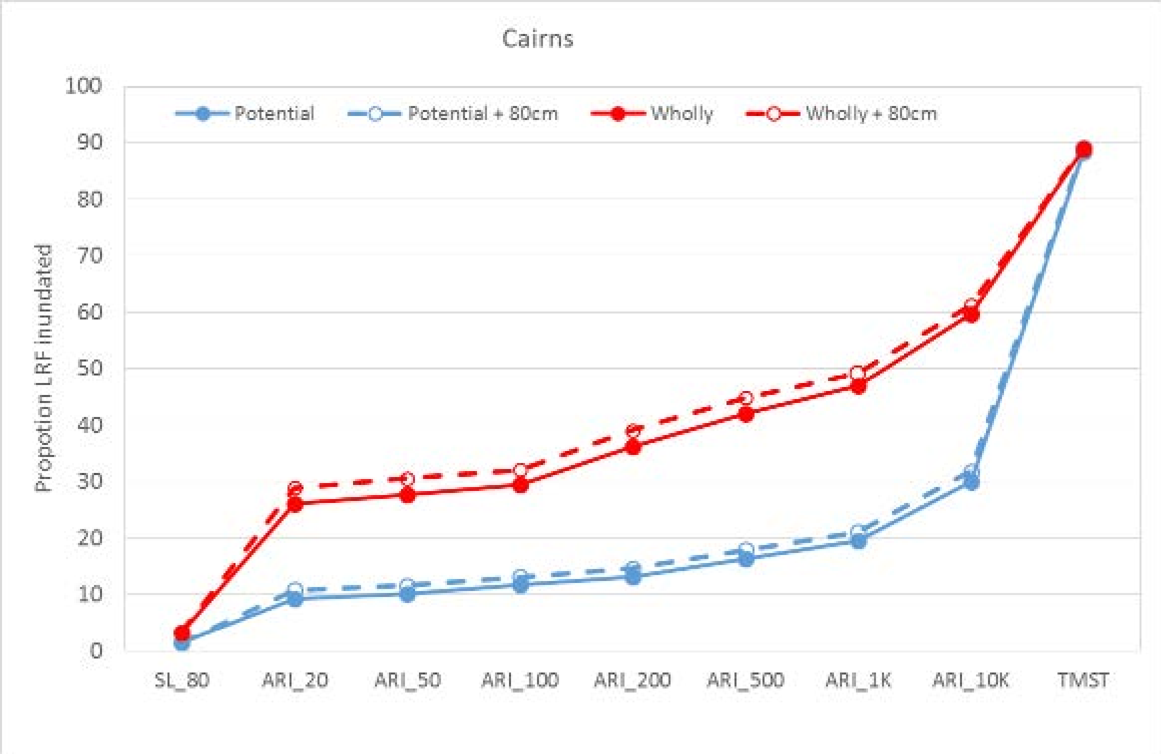



Townsville
Potential
Potential + 80cm
Wholly
Wholly + 80cm
Propotion LRF inundated
100
90
80
70
60
50
40
30
20
10
0
SL_80
ARI_20
ARI_50
ARI_100
ARI_200
ARI_500
ARI_1K
ARI_10K
TMST


Hinchinbrook
Potential
Potential + 80cm
Wholly
Wholly + 80cm
Propotion LRF inundated
100
90
80
70
60
50
40
30
20
10
0
SL_80
ARI_20
ARI_50
ARI_100
ARI_200
ARI_500
ARI_1K
ARI_10K
TMST


Cassowary Coast
Potential
Potential + 80cm
Wholly
Wholly + 80cm
Propotion LRF inundated
100
90
80
70
60
50
40
30
20
10
0
SL_80
ARI_20
ARI_50
ARI_100
ARI_200
ARI_500
ARI_1K
ARI_10K
TMST


Yarrabah
Potential
Potential + 80cm
Wholly
Wholly + 80cm
Propotion LRF inundated
100
90
80
70
60
50
40
30
20
10
0
SL_80
ARI_20
ARI_50
ARI_100
ARI_200
ARI_500
ARI_1K
ARI_10K
TMST



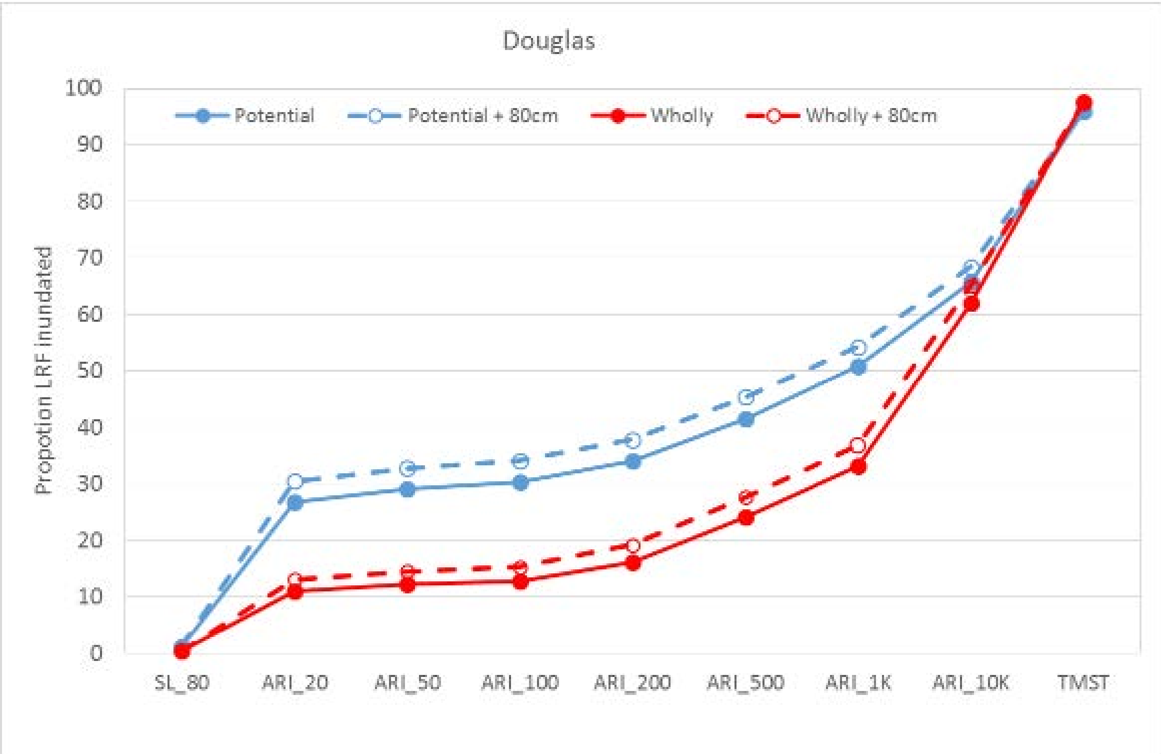
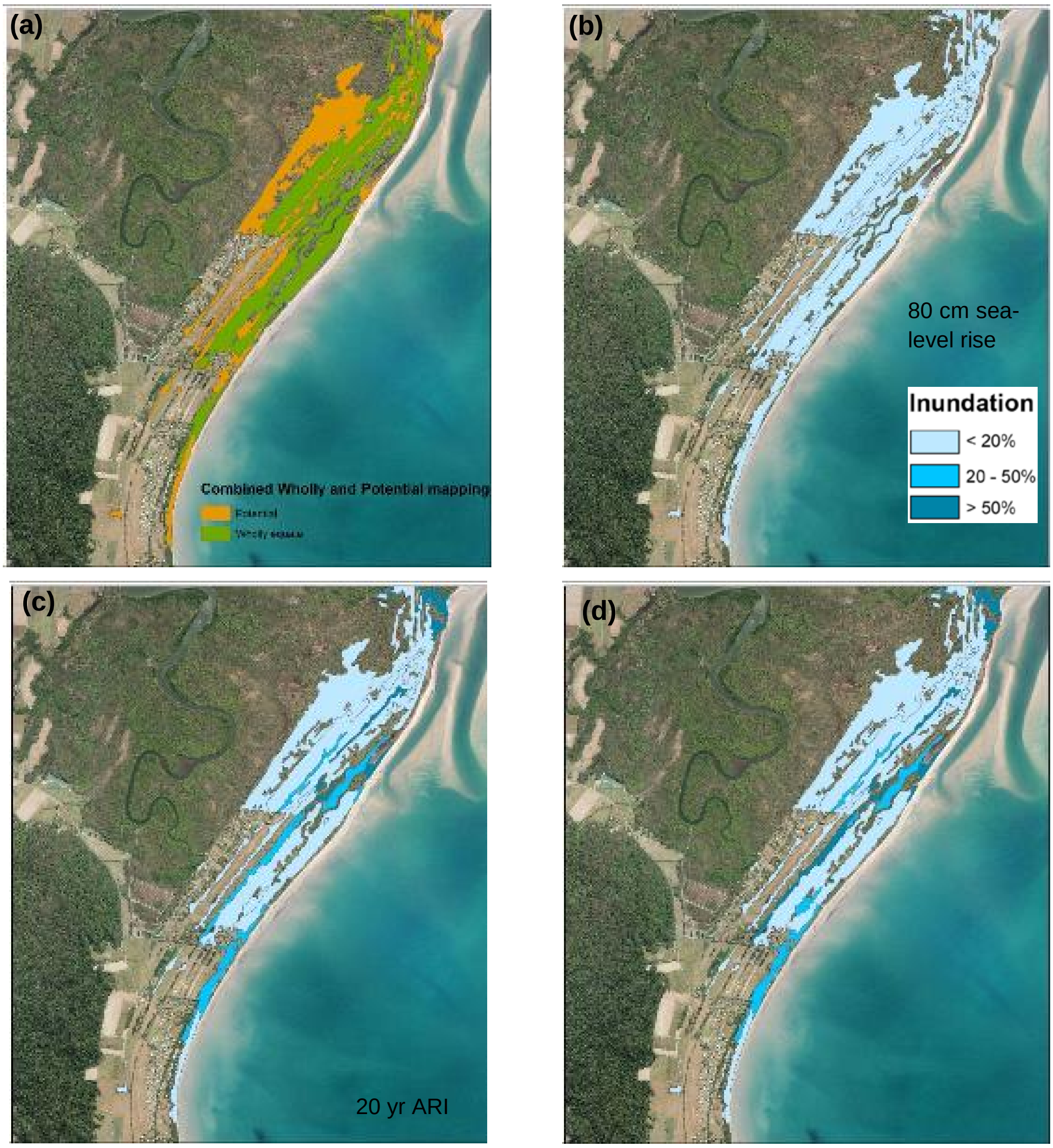
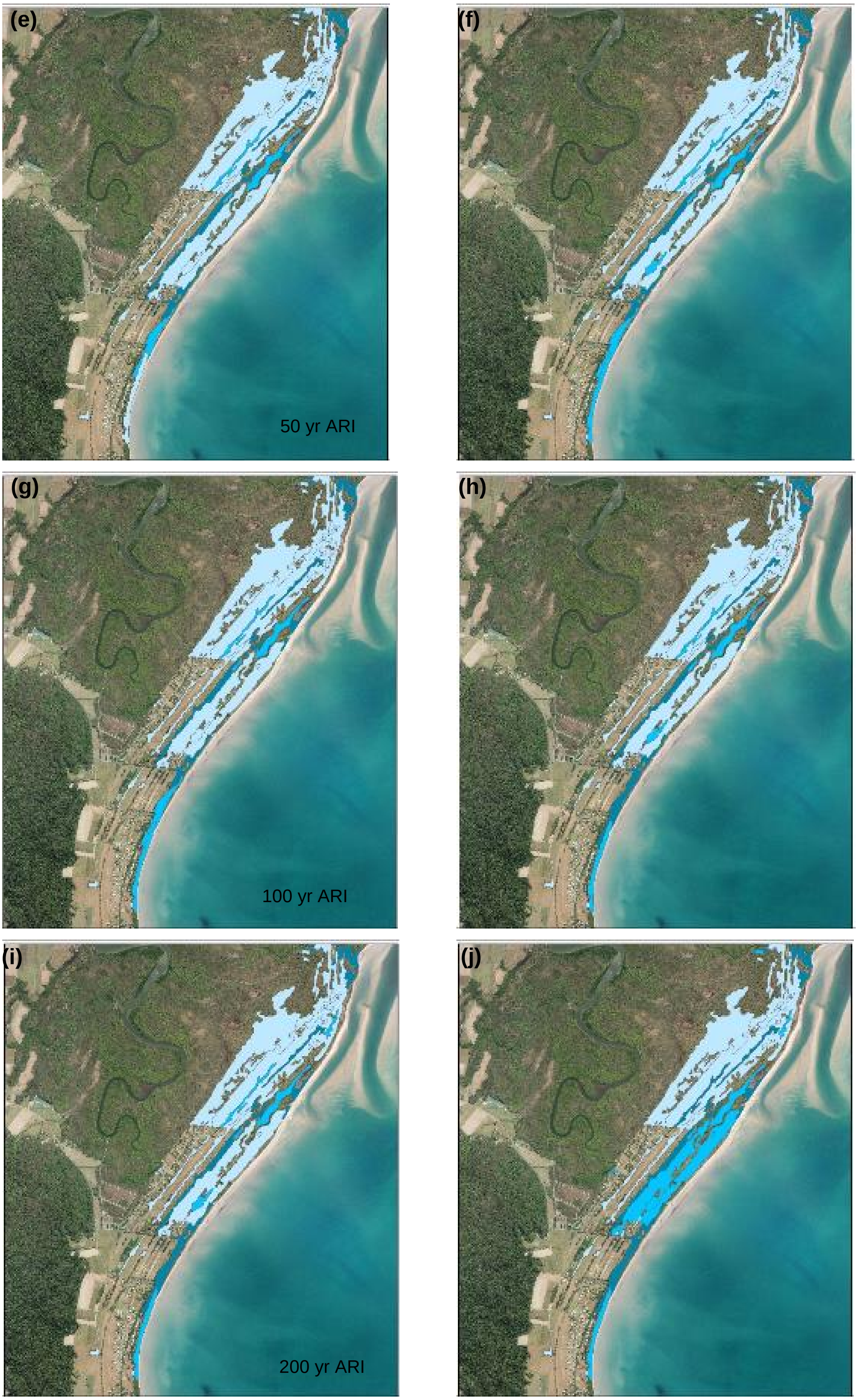


Figure 3 Proportion of LRF inundated in each Local Government Area in the study area.
The proportion of LRF inundated is shown separately for Wholly LRF with and without 80 cm sea-level rise and for Potential LRF with and without 80 cm sea-level rise. SL_80 reflects the inundation level for sea-level rise only; ARI_20 reflects the inundation level for an ARI of 20 years, etc. TMST = Theoretical Maximum Storm Tide. The Cook region is not shown here because the LiDAR data did not cover enough of the assessable area.

We created spatial layers of inundation at the patch scale for another perspective on the extent of inundation (Figure 4 and Figure 5). Patches were defined by the RE mapping and are potentially a useful unit for management.




(e)
50 yr ARI
(f)
(g)
100 yr ARI
(h)
(i)
200 yr ARI
(j)


(k)
500 yr ARI
(l)
(m)
1000 yr ARI
(n)
(o)
10,000 yr ARI
(p)

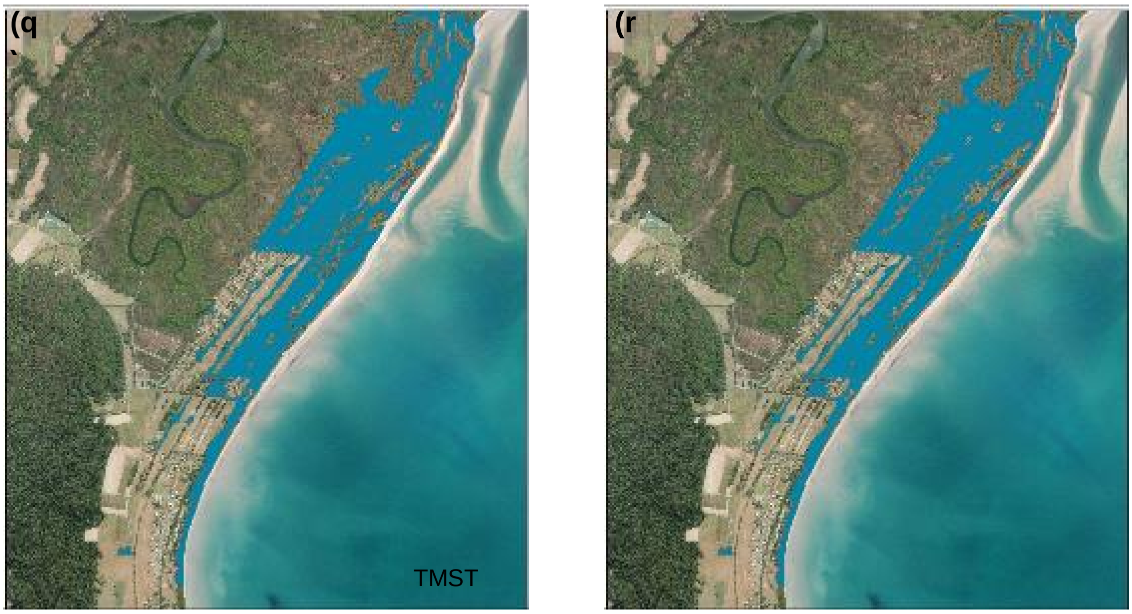


Figure 4 Example of spatial layers available for inundation mapping.
Panel (a) shows the location of wholly and potential LRF in a location north of Port Douglas. Panel (b) shows the proportion of a patch inundated with an 80 cm sealevel rise. Panels (c) through (r) show the proportion of a patch (determined as per the RE mapping) inundated under the different ARI levels without sea-level rise (Left column) and with an 80 cm sea-level rise (Right column).

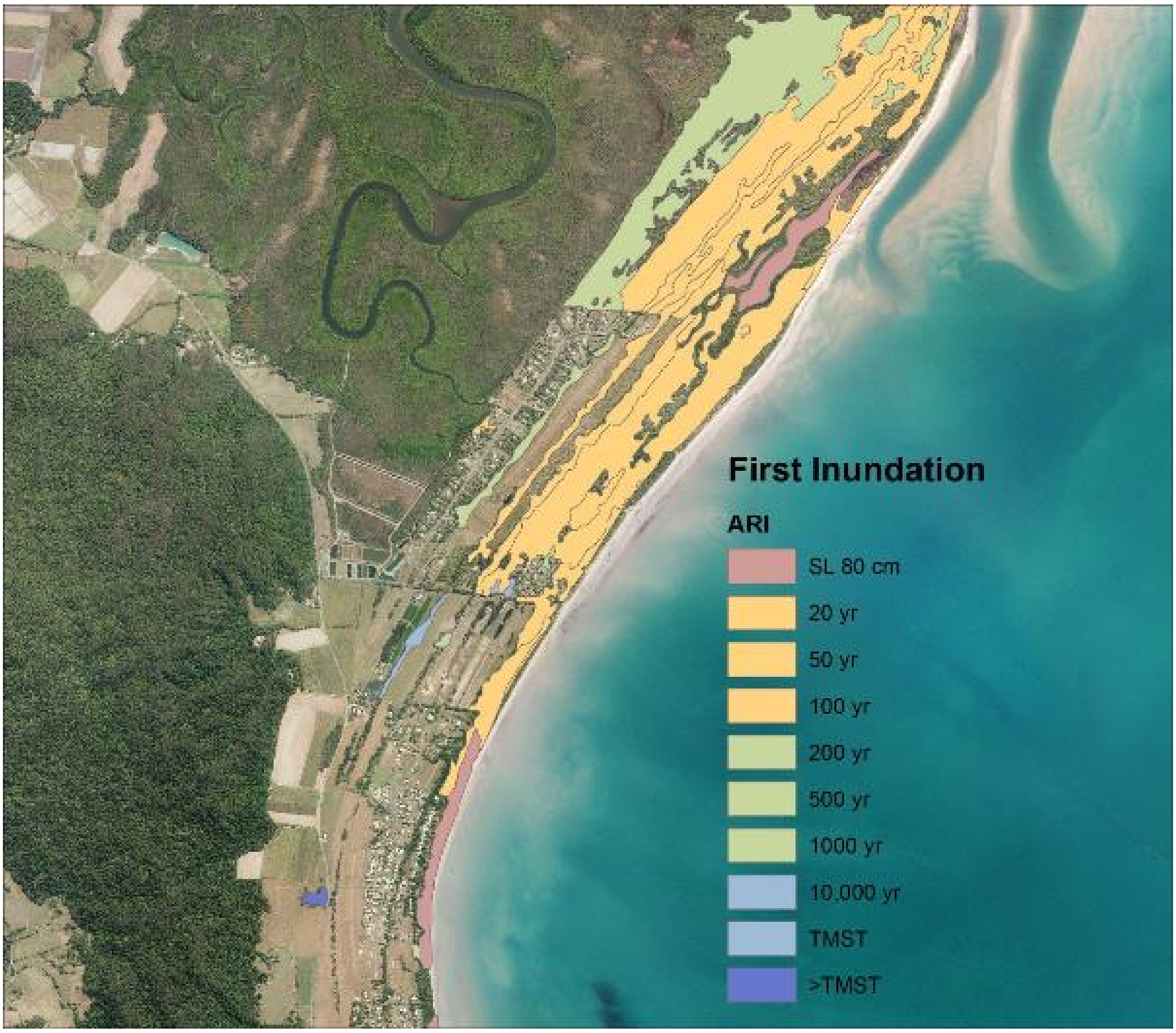


Figure 5 The figure shows the ARI level at which a patch first becomes inundated.
SL 80 cm indicates inundation with an 80 cm sea level rise. Orange indicates relatively frequent inundation (ARIs between 20 and 100 years), green is relatively infrequent (ARIs between 200 and 1000 years) and the blue shading indicates inundation only under extreme conditions (ARIs 10,000 years and the Theoretical Maximum Storm Tide). >TMST indicates where a patch doesn't become inundated even under the TMST.

4. Management of Littoral Rainforest

The Expert Advisory Committee (EAC) convened for this Wet Tropics project (see Acknowledgements) noted that in terms of on-ground management and planning, the most important information to have at hand was the actual location of LRF in their jurisdiction. Previously, due to a lack of clarity in the Listing Advice, even this basic spatial data has not been available, except in the Mission Beach pilot area where it is now online and frequently referred to for information purposes. Mapping allows staff managing National Parks and Council reserves to better plan for management of pressures and threats and to undertake restoration and revegetation, enables Local Government to consider the location of LRF in planning schemes and development approvals, enables the Australian Government to do planning and compliance work, enables NRM bodies to strategcially distribute available MNES resources, and raises awareness of private landholders.

Wholly-equate vegetation constitutes an explicit mapping of the Regional Ecosystems listed in the Listing Advice. We know that considerable areas that meet the description and condition thresholds in the Listing Advice are not captured by the wholly-equate method. The Potential LRF layer indicates where the broad characteristics of LRF described in the Listing Advice are met and therefore LRF may occur. However, only on-ground assessments can establish whether the Listing Advice's description and condition thresholds are met. Extensive areas of potential LRF primarily occur on coastal sand deposits, and are frequently adjacent to existing Littoral rainforest where they are often mapped as sclerophyllous REs. It is anticipated that the majority of these communities that currently have sclerophyllous elements will eventually transition to LRF in the absence of fire, thus potential LRF can play a significant role in the recovery and conservation of local Littoral rainforest, especially in adjacent areas on sand which have undergone transition due to severe disturbance (e.g. cyclones, clearing). These potentially new areas of Littoral rainforest must be assessed on a case by case basis for consideration as current Littoral rainforest.

Potential areas of Littoral rainforest also exist in areas that have additional and exceptional circumstances associated with the current RE mapping. These circumstances include Littoral rainforest on substrates other than sand, acidic granitic rocks and metamorphic rocks. In the Clump Point area near Mission Beach, it has been shown that it is possible to map a fringe of Littoral rainforest on basalt immediately above the mean high tide mark, which has significantly different floristic assemblages to the adjacent rainforest on basalt. Thus, consideration needs to be extended into additional land zones (i.e. basalt is land zone '8' in the RE terminology).

The spatial data provided by this report can be used for prioritisation of LRF for recovery planning. Consideration should be given to the extent of current pressures, the current level of protection and management of pressures, the exposure to future pressures including that from storm-surge and sea-level rise, the capacity of the vegetation to autonomously regenerate and the capacity of the ecological community to adapt by shifting or migrating inland and/or upslope.

4.1 Current pressures

The presence and intensity of impacts to LRF in the study area is varied and difficult to quantify. Although the REs which make up LRF in the Wet Tropics and southern Cape York bioregions are generally resilient communities (being located in or adjacent to the naturally dynamic littoral zone) they do suffer impacts from a variety of sources. Virtually the entire study area has been affected by at least one category 3 cyclone. In 2011 Cyclone Yasi (category 5) damaged a massive area between Cairns and Townsville. Cyclone Ita (category 4) crossed land north of Cooktown in early 2014 but weakened quickly, thus reducing its effect in the area, with the exception of Lizard Island. Assessments in the Cooktown area failed to find any strong signature from Cyclone Ita, unlike further south where the signature from Cyclone Yasi is still very evident.

Cyclones also bring storm surges in the form of both higher than usual high tides and destructive wave action, which cause beach erosion but also deposit large volumes of beach sands in other places. Beach erosion was extreme in several places (e.g. the Cape Kimberley area north of the Daintree River), with mature *Calophyllum inophyllum* trees now lying on the strand completely uprooted with their roots exposed from undermining. Sand deposition, often with coral debris, was also seen in several places with Russell Island (near Innisfail) gaining up to one metre of new dune height which is being recolonised by *Casuarina equisetifolia.*

A total of 39 weed species were recorded and weed species occurred in 64% of the sites we surveyed (Table 5 and see details in **Appendix B.**). The most common species recorded was *Cocos nucifera* (Coconut) which occurred in 34% of the sites. Singapore Daisy (*Sphagneticola trilobata*) was the next most commonly occurring species (17% of sites). Ten of the species we recorded are considered “Transformer Species” in the Listing Advice for LRF for the Wet Tropics.

In a few sites, recent clearing of LRF has occurred, including road construction to the beach and real-estate development. Because the vegetation has been completely removed, this land clearing should be seen as the most significant impact to LRF communities. The flow-on effect of clearing is that it is usually accompanied by weed invasion on the newly exposed and disturbed LRF edges, and there is a greater potential for a low intensity fire to further erode the edges.

A number of designated National Park and Council camping and picnic areas in coastal areas and Islands of the Wet Tropics are located within LRF. All such areas usually have infrastructure (toilets) and tracks to them, from which the vegetation is periodically trimmed for management purposes.

Beach access and recreational driving on sand deposits is a major impact to the development and sustainability of LRF adjacent to built-up areas. In these areas (e.g. Rollingstone Beach) the recreational tracks wind between trees of LRF, reducing future recruitment and increasing the weedy edges. Walking track beach access and clearing or thinning for sea views, although regulated in most places, has been noted as having a significant impact on some sites, especially where the tracks or clearings have been made and maintained by adjacent landholders to the beach. Most of the vegetation cleared and trimmed is frequently within local council reserves and esplanades.

Other minor impacts include: cattle, pigs, fire, parking areas (unregulated) and presence of myrtle rust (e.g. Hinchinbrook Island, host was *Eugenia reinwardtiana*).

Table 5 Presence of weed species in sites surveyed (of 156 sites). The column 'Listing Advice' indicates if the species is considered a transformer species in the Listing Advice for the community.

No weeds	56 sites	
Species	**Number of sites**	**Listing Advice**
Cocos nucifera	53	
Sphagneticola trilobata	27	Transformer
Passiflora foetida	23	Transformer
Lantana camara	18	Transformer
Passiflora suberosa	16	Transformer
Praxelis clematidea	9	
Annona glabra	8	Transformer
Mangifera indica	5	
Stachytarpheta sp.	5	
Megathrysus maximus	5	Transformer
Crotalaria pallida	5	
Catharanthus roseus	4	
Hyptis suaveolens	3	Transformer
Acanthaceae	3	
Triumfetta sp.	3	
Tradescantia spathacea	2	
Syngonium podophyllum	2	
Cenchrus echinatus	2	Transformer
Opuntia sp.	2	Transformer
Emilia sonchifolia	2	
Murraya paniculata cv exotica	2	
Melinus repens	2	
Ipomoea indica	1	
Mimosa pudica,	1	
Cleome sp.	1	
Sansevieria trifasciata	1	
Cordyline sp.	1	
Stylosanthes sp.	1	
Tridax procumbens	1	
Themeda quadrivalvis	1	
Carica papaya	1	
Melinus minutiflorus	1	Transformer
Axonopus compressus	1	
Leucana leucocephala	1	
Ipomoea hederifolia	1	
Solanum seaforthianum	1	
Sida cordifolia	1	
Alternanthera brasiliensis	1	
Axonopus compresses	1	
Other Grasses (e.g. Para Grass)	5	

Beach access tracks through Littoral rainforest inhibit recruitment of species and damage root systems (Credit: Andrew Ford).

A beach shanty in an area mapped as Littoral rainforest (Credit: Andrew Ford)

Photo taken adjacent to Site 29 (see Appendix B). Site 29 was confirmed as LRF in the field, however the RE mapping describes it (incorrectly) as non-remnant vegetation. Clearing for a residential development had recently taken place along the edge of the vegetation, highlighting how a reliance on RE mapping and the lack of a clear delineation of Littoral rainforest in LGA planning schemes can result in inadvertent impacts. (Credit: Helen Murphy)

Singapore Daisy (Sphagneticola trilobata) in the understorey of Littoral rainforest (Credit: Andrew Ford)

Figure 6 Photos of impacts to LRF observed during field work

4.2 Land use and tenure

The majority of both wholly-equate and potential LRF is contained within landuse classified as Conservation and Natural Environments according to Queensland's current land use mapping (QLUMP 2016) (Figure 7). This is not surprising since LRF will have been largely removed already from areas under intensive use or agricultural production. However, the classification 'conservation and natural environments' includes a wide range of tenures (as can be seen in Figure 8) and uses including National Parks, Defence land, resource use and 'other minimal use'.

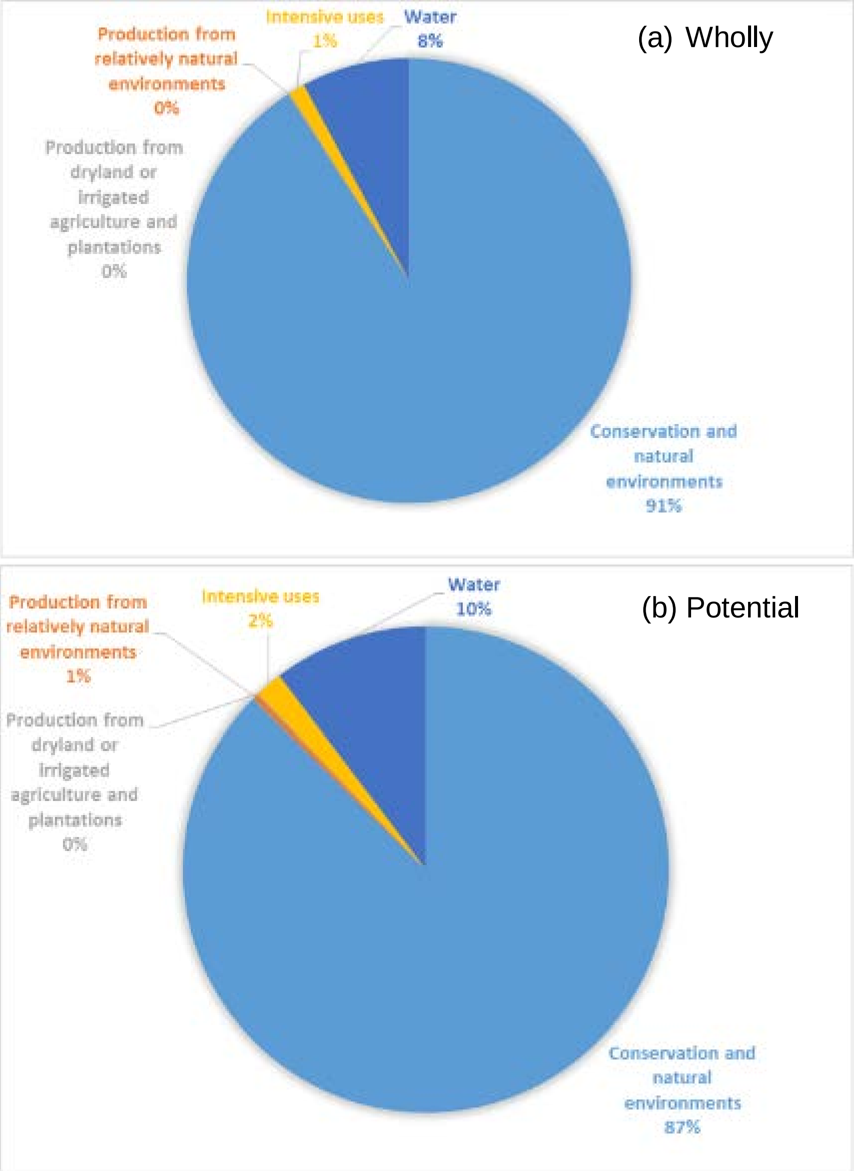
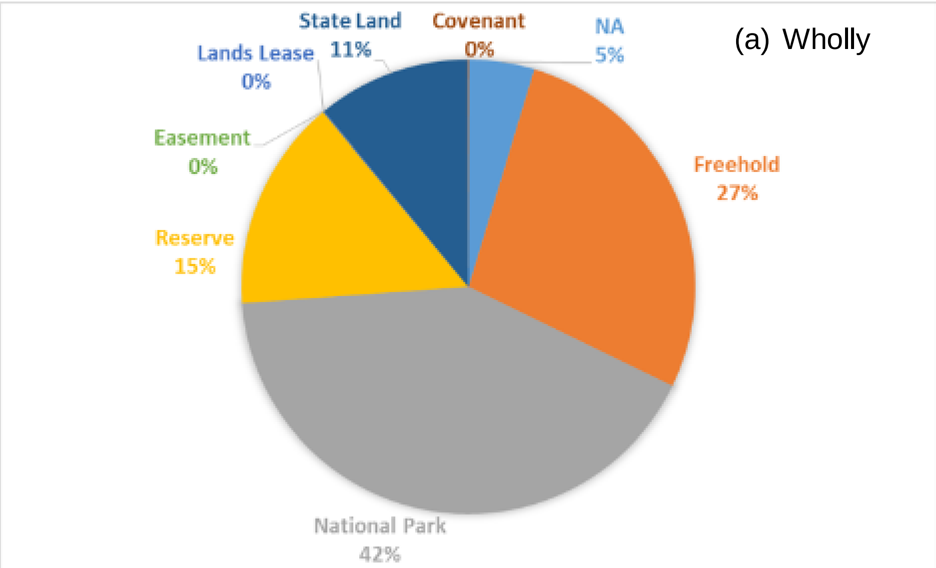


Figure 7 The distribution of (a) wholly-equate LRF and (b) potential LRF in different land use classes across the study area.

The majority of both wholly-equate and potential LRF in the study region is contained with National Park tenure, with a further 26% of wholly and 20% of potential contained within Reserve or State Land (Figure 8). However a significant portion (27%) is contained within Freehold tenure. The distribution of LRF in tenure varies throughout the region (Figure 9).

The Cassowary Coast has relatively more LRF contained in National Park than Freehold, whereas Douglas Shire has more LRF contained in Freehold tenure. Littoral rainforest in the Aboriginal Councils of Palm Island, Yarrabah and Hope Vale is almost exclusively contained in Freehold tenure.

The Expert Advisory Committee agreed that LRF that was already in the conservation estate was generally subject to fewer current threats and these threats were often managed. For example, impacts from weeds and pest animals, and human-mediated pressures were managed or regulated in day-to-day operations. The councils of Yarrabah, Hope Vale and Palm Island, where LRF is contained within the Freehold estate, have relatively low population density and likely have fewer anthropogenic pressures (though this has not been assessed in this study). However, resources for management following extreme storm events are likely to be limited in these council areas and therefore they should be considered for priority investment in the event of significant impacts from storm-surge.



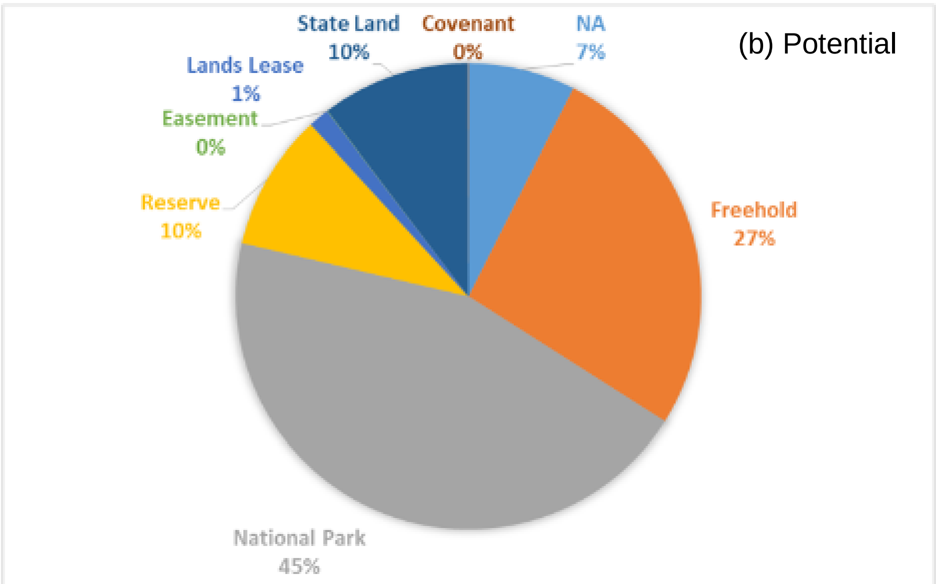
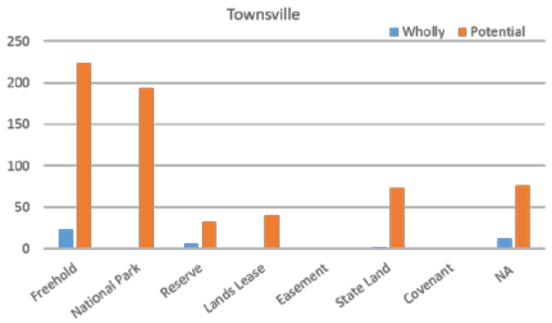
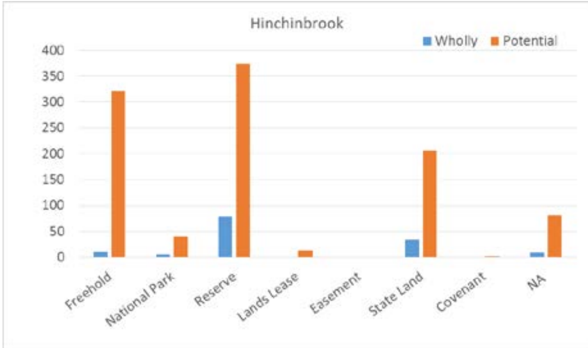
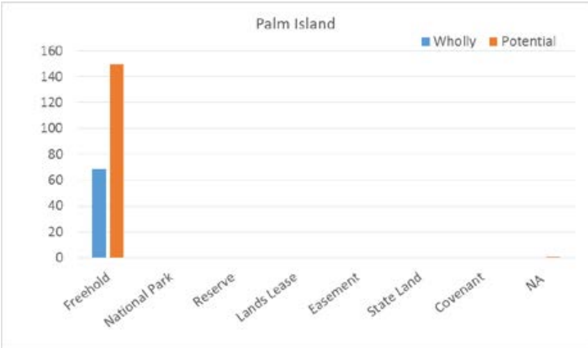
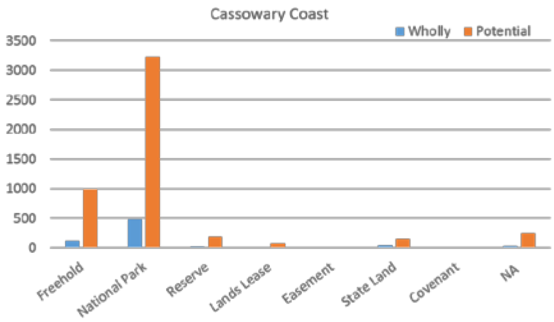


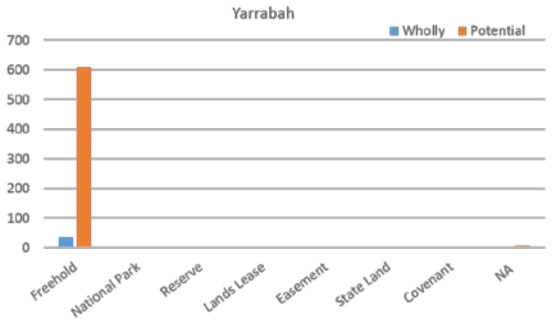
Figure 8 Distribution of (a) wholly-equate and (b) potential LRF across tenure in the study area

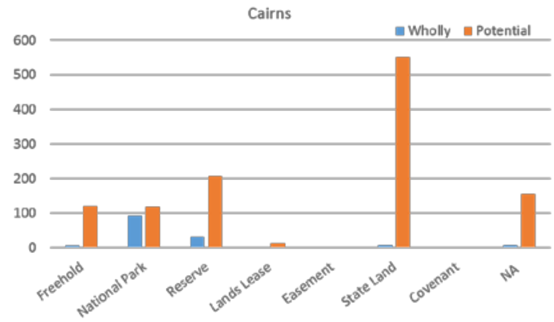

Townsville
Wholly
Potential
250
200
150
100
50
0
Freehold
National Park
Reserve
Lands Lease
Easement
State Land
Covenant
NA

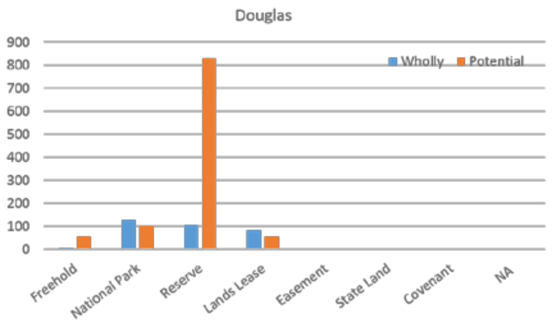

Hinchinbrook
Wholly
Potential
400
350
300
250
200
150
100
50
0
Freehold
National Park
Reserve
Lands Lease
Easement
State Land
Covenant
NA

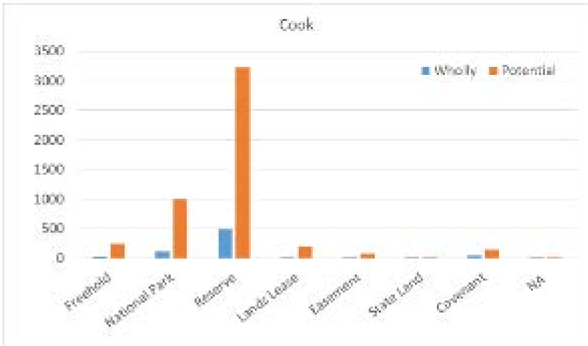

Palm Island
Wholly
Potential
160
140
120
100
80
60
40
20
0
Freehold
National Park
Reserve
Lands Lease
Easement
State Land
Covenant
NA


Cassowary Coast
Wholly
Potential
3500
3000
2500
2000
1500
1000
500
0
Freehold
National Park
Reserve
Lands Lease
Easement
State Land
Covenant
NA


Yarrabah
Wholly
Potential
700
600
500
400
300
200
100
0
Freehold
National Park
Reserve
Lands Lease
Easement
State Land
Covenant
NA


Cairns
Wholly
Potential
600
500
400
300
200
100
0
Freehold
National Park
Reserve
Lands Lease
Easement
State Land
Covenant
NA


Douglas
Wholly
Potential
900
800
700
600
500
400
300
200
100
0
Freehold
National Park
Reserve
Lands Lease
Easement
State Land
Covenant
NA


Cook
Wholly
Potential
3500
3000
2500
2000
1500
1000
500
0
Freehold
National Park
Reserve
Lands Lease
Easement
State Land
Covenant
NA

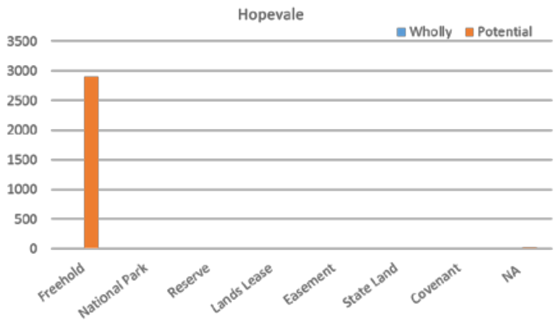


Figure 9 Distribution of wholly and potential LRF in different tenures in each LGA. The vertical axis represents hectares

4.3 Sea-level rise and storm surge

The spatial layers depicting the extent of inundation at different ARI levels (Figure 4) indicate the level of exposure to future pressures from storm-surge and sea-level rise. However, the relative effect of wind and storm surge is unclear and it is almost impossible to predict how much damage to the vegetation will actually be caused by cyclones associated with a storm surge. Vegetation will be impacted by cyclonic winds, and storm surge impacts will be determined by the depth of inundation, the force of the surge and associated waves and their retreat, the duration of inundation, the movement of sand and erosion effects, and the original structure of the vegetation.

Cyclone Yasi was considered to have created between 1000 yr (Clump Point) and 3000 yr (Cardwell) ARI (GHD Pty Ltd 2014) and crossed Cardwell as a category 5 cyclone. Examples of the subsequent severe damage to Littoral rainforest can be seen in Figure 10 and are described in the previous section.

Impacts on LRF post Cyclone Yasi at Tully Heads (Credit: Dan Metcalfe)

Wongaling Beach showing coastal retreat by ~40m post-cyclone Yasi – recent observations show the beach being recolonised by vegetation including LRF species (Credit: Dan Metcalfe)

Pond Apple (Annona glabra) recruitment in LRF post-cyclone (Credit: Dan Metcalfe)

Over-zealous clearing of cyclone damaged LRF post-cyclone Yasi (Credit: Dan Metcalfe)

Clearing and removal of damaged vegetation by local residents post-cyclone Yasi (Credit: Dan Metcalfe)

Figure 10 Photos showing impacts to LRF during and post-cyclone

4.4 Room to move; natural capacity to recover

In many coastal margins, natural features as well as urban and rural development and infrastructure prevent shoreward migration of coastal ecosystems, such that sea-level rise will result in increasingly narrow distributions ('coastal squeeze') (Figure 11). Restoring and stabilising Littoral rainforest substrates in areas increasingly exposed to storm surge or sea-level rise, without providing an avenue for vegetation migration, undermines the capacity for natural recovery and for future adaptation.

Other pressures that cause disturbance to the understorey (e.g. access tracks, driving, slashing/mowing etc) as well as pressures such as weed and feral animal invasion, also undermine the natural capacity of the vegetation to recover following disturbance.

Figure 11 Coastal squeeze – LRF adjacent to a residential development and natural feature (river) with no room to move

4.5 Refugia, buffers and the leading-edge

Littoral rainforest is adapted to, and may even benefit from, low-level inundation, however an increasing frequency of inundation is likely to cause some mortality, hamper recruitment and ultimately alter the structure of Littoral vegetation. More severe exposure events, particularly those associated with severe cyclones, will have a range of impacts which will partly be dependent on the pre-event condition and structure of the vegetation which determine its resilience.

Our mapping and inundation analysis can be used to define a number of different roles of LRF in the landscape on which a portfolio of management approaches can be derived which allow for the short-, medium- and long-term effects of sea-level rise and storm surge in multi-use landscapes. We define Refugial, Buffer and Leading-Edge LRF patches by the relative frequency at which they become inundated (Table 6) and suggest management actions to take account of the different roles and improve resilience of the community as a whole (Table 7).

'Leading-edge' patches are frequently inundated (up to 100 yr ARI), 'buffer' patches are inundated less frequently (200 – 1000 yr ARI), and 'refugial' patches are infrequently inundated (>10,000 yr ARI). At the patch level, the frequency of inundation could be defined in a number of ways depending on the extent of inundation caused by a given ARI in a patch. For example, Table 6 shows that 80% of LRF falls into the leading-edge category if we consider that a patch is impacted if an ARI results in any inundation (i.e. the area of all patches that experience more than 1% inundation divided by the total area of LRF), with only 7% falling into the refugia category. With the addition of an 80 cm sea–level rise, 91% of LRF falls into the leading-edge category. Alternatively, we could consider that a patch is impacted if an ARI results in >20% inundation; in this case only 25% of LRF falls into the leading-edge category and 53% into the refugia category. With a 50% threshold the proportion in the refugia category is higher still (83% without sea-level rise and 81% with sea-level rise). The example shown in Figure 12 shows the three categories based on the >20% inundation level. This level of inundation seems a reasonable middle-ground from which to consider the various categories because 20% inundation is likely to cause some level of damage to vegetation and be associated with potentially more extreme events that also cause damage from wind.

Table 6. The proportion of leading-edge, buffer and refugia LRF in the study area. >1% indicates the proportion of LRF in each category if considering that an ARI causes any inundation. Subsequent columns indicate the proportion of LRF in each category if considering that an ARI causes >20% inundation or >50% inundation. Proportions are shown with and without 80 cm sea-level rise.

	Inundation	Without sea-level rise			With 80 cm sea-level rise		
		>1%	>20%	>50%	>1%	>20%	>50%
Leading edge	Frequent – 80 cm sea-level rise, and 20, 50 and 100 yr ARIs	80	25	7	91	30	10
Buffer	Moderate - 200, 500, and 1000 yr ARIs	13	22	10	3	20	9
Refugia	Infrequent – 10,000 yr ARI, TMST and >TMST	7	53	83	6	50	81

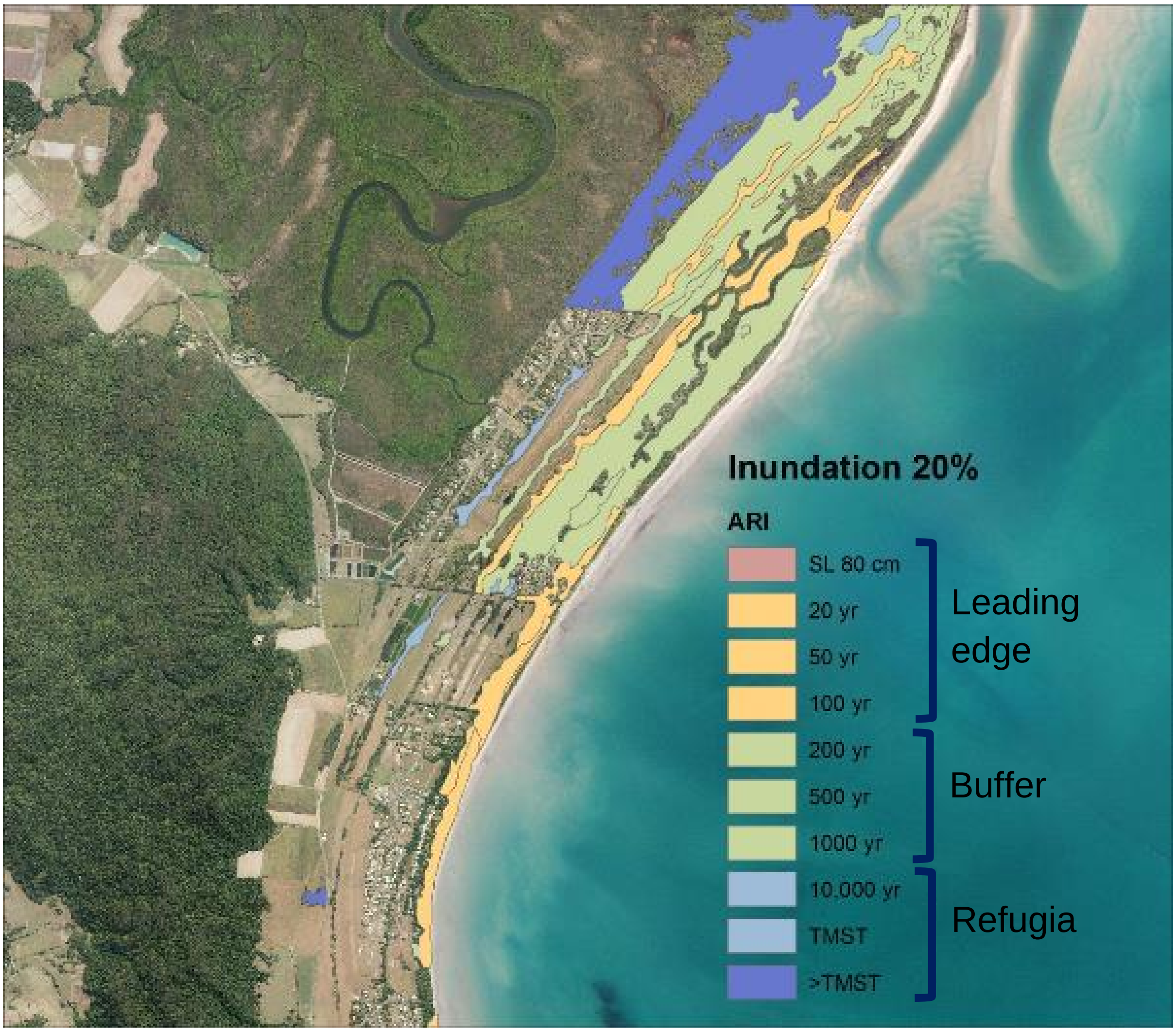


Figure 12 Leading-edge, buffer and refugia LRF based on the ARI in which a patch experiences greater than 20% inundation

4.5.1 Manage and protect refugia

Natural refugial areas of LRF are found in areas that are not frequently inundated and have the capacity to persist in the long-term, even under fairly extreme conditions. Identifying, protecting and managing LRF in these areas is critical to enhance the capacity for long-term persistence of the community. Refugial areas in tenure other than National Park or Reserve should be considered for inclusion in the Protected Area Estate. Refugial areas should also be prioritised to relieve anthropogenic pressures and for restoration where they have become degraded. Refugial areas are good targets for revegetation aimed at expanding the size of patches and reducing fragmentation. Revegetation should be with appropriate species for the substrate and locality.

4.5.2 Enhance resilience of the leading-edge

Leading-edge vegetation is exposed to inundation frequently; it becomes inundated at 80 cm sea-level rise and at ARIs between 20 and 100 years. Often this vegetation is closest to the foreshore or in depressions behind the foreshore. In some cases, leading-edge vegetation occurs further inland in lower lying areas behind the dunes. Leading-edge vegetation can be critical in providing ecosystem and climate adaptation services; protecting and buffering human communities from the effects of storm-surge, sea-level rise and other impacts of extreme storm events. Planners and managers should prioritise management in locations that provide the most critical services, and should protect and restore these locations to sustain these services. Managing existing pressures in leading-edge vegetation will enhance the capacity of the community to recover following disturbance and enable the continued provision of services.

Restoration actions may be necessary to speed recovery times, restore diversity, and maintain the size and condition of the patch following inundation. Ultimately, as the substrate becomes increasingly eroded and the patch becomes more disturbed, ecosystem and adaptation services will be significantly diminished in the absence of planning that allows for the substrate and vegetation to shift naturally.

In many areas, leading-edge vegetation occurs in areas where the substrate and vegetation has room to retreat inland as sea-level rises and after exposure to inundation. In this case few management actions are necessary other than ensuring planning mechanisms continue to provide room to move, and management of pressures where necessary.

4.5.3 Manage the buffer zone to enhance connectivity

Buffering vegetation is inundated moderately frequently (i.e. in ARIs from 200 to 1000 years). In some areas buffer vegetation occurs behind leading-edge vegetation or other coastal vegetation types (e.g. mangroves); however it may also occur as the first line of vegetation on slightly elevated dunes. In these latter circumstances it may also buffer refugial vegetation. Buffer vegetation that provides critical ecosystem and adaptation services should be a high priority for restoration and management of pressures to enhance resilience.

In some areas, buffer vegetation plays a very important role in ensuring connectivity between refugial and leading-edge vegetation. In these areas, managing pressures and restoring degraded areas should be a priority in order to enhance resilience of the leading-edge vegetation (e.g. by acting as a seed source of native species for regeneration) and in ensuring continuity of some adaptation services following frequent but low-level storm surge.

Table 7. The role of LRF in the landscape and relevant management actions

LRF role	Characteristics	Management actions
Refugial	Exposed infrequently	• Consider enhanced/formal protection status for areas not in the Protected Area Estate • Rehabilitate degraded patches and enhance size and connectivity of patches • Reduce pressures (e.g. invasive species, access impacts)
Buffer	Exposed moderately to infrequently	• Consider enhanced/formal protection status for areas not in the Protected Area Estate that are critical for connecting leading-edge and refugial areas • Manage pressures (e.g. invasive species, access impacts) • Prioritise restoration in areas where buffer vegetation provides connectivity between leading-edge and refugial vegetation or where it provides critical services
Leading-edge	Exposed frequently	• Prioritise management in areas where critical services are provided • Stabilisation and/or facilitated natural colonisation to speed recovery following inundation impacts in areas providing critical services • Formalise planning mechanisms to allow retreat in areas not already developed

5. Conclusions and recommendations

We have undertaken a survey of the distribution and condition of LRF in the Wet Tropics and southern Cape York bioregions between Townsville and Cooktown.

The following spatial layers were derived and are available at the CSIRO data portal:

- LRF vegetation that 'wholly-equates' to the EPBC Listing Advice
- 'Potential' LRF delineating areas consistent with broad characteristics of the community described in the EPBC Listing Advice
- Inundation statistics for each patch of wholly-equate LRF and potential LRF (patches defined by RE mapping) indicating:
  - the proportion of each patch inundated with 80 cm sea-level rise
  - the proportion of each patch inundated at each of 8 ARIs with and without sea-level rise
  - the ARI at which a patch first becomes inundated
  - the ARI at which a patch is >20% inundated
  - the ARI at which a patch is >50% inundated

The methodology we describe here for defining wholly-equate and potential LRF could be applied to the remainder of Queensland where RE mapping is available. Regionally-specific modifications to the 'Rules' we used for mapping would likely be required. It is clear that there is no substitute for on-ground assessment in both the wholly-equate zone and potential LRF zone since errors in the RE mapping do exist and scale issues mean that LRF may or may not occur precisely where the mapping dictates.

Some further recommendations are provided below, many of which build from those identified in the Mission Beach Pilot Study.

We recommend that:

- Both the wholly-equate and potential LRF layers are considered in the Recovery Planning process in terms of resource allocation, and in development planning, assessment and compliance.
- Australian Government consider both wholly-equate and potential LRF layers in implementing the EPBC Act.
- The Recovery Planning process recognises the occurrence of LRF in some of the most contested, dynamic, multi-use landscapes of the region's coastal councils – i.e. the foreshore, and considers appropriate resourcing for improving management capacity particularly within Local Regional Councils, Aboriginal Shires and Regional NRM groups of the region.
- The Recovery Planning process includes a strategy for raising awareness of the role of LRF in the coastal landscape and engaging stewards in its management.
- Refugial LRF is considered a high priority for formal protection where this is not already the case.
- State land managers and Local Councils consider both wholly-equate and potential LRF layers in their biodiversity strategies and land use planning, resource allocation for invasive species and access management, revegetation and restoration, and cyclone response and preparedness.

- State agency land managers (including managers of the conservation estate) undertake on-ground assessments of vegetation in the wholly and potential LRF layers to further delineate the location of LRF within their management area.
- Future revision of Regional Ecosystem definitions and boundaries recognise RE subtypes that reflect mosaics potentially containing LRF.
- The indicative species list in Attachment A of the Listing Advice be updated as per the suggestion in Section: Species lists.
- The list of transformer weeds specific to the Littoral rainforests of the Wet Tropics be updated considering the range and abundance of species recorded during this study
- The recommendations and mapping in Metcalfe *et al.* 2014 also be considered.

6. References

Barbier E. B., Koch E. W., Silliman B. R., Hacker S. D., Wolanski E., Primavera J., Granek E. F., Polasky S., Aswani S., Cramer L. A., Stoms D. M., Kennedy C. J., Bael D., Kappel C. V., Perillo G. M. E. & Reed D. J. (2008) Coastal Ecosystem-Based Management with Nonlinear Ecological Functions and Values. *Science* **319**, 321-3.

Department of the Environment, Water, Heritage and the Arts (2009) Advice to the Minister for the Environment, Water, Heritage and the Arts from the threatened Species Scientific Committee (the Committee) on Amendments to the List of Ecological Communities under the Environment Protection and Biodiversity Conservation Act 1999 (EPBC Act). Department of Environment, Canberra. Available at http://www.environment.gov.au/biodiversity/threatened/communities/pubs/76-listing-advice.pdf [cited 11 May 2016].

Department of the Environment (2016) Littoral Rainforest and Coastal Vine Thickets of Eastern Australia in Community and Species Profile and Threats Database, Department of the Environment, Canberra. Available at: http://www.environment.gov.au/sprat [cited 11 May 2016]

GHD Pty Ltd (2014) NDRP Storm Tide Hazard Interpolation Study. Report to the Queensland Department of Science, Information, Technology, Innovation and the Arts.

Lavorel S., Colloff M. J., McIntyre S., Doherty M. D., Murphy H. T., Metcalfe D. J., Dunlop M., Williams R. J., Wise R. M. & Williams K. J. (2015) Ecological mechanisms underpinning climate adaptation services. *Global Change Biol.* **21**, 12-31.

Metcalfe, D.J., O'Malley, T., Lawson, T.J. and Ford, A.J. (2014) *Mapping Littoral Rainforest and Coastal Vine Thickets of Eastern Australia in the Wet Tropics: Mission Beach Pilot Study.* Report to the National Environmental Research Program. Reef and Rainforest Research Centre Limited, Cairns (37 pp.)

Queensland Herbarium (2015) Regional Ecosystem Description Database (REDD). Version 9.0 (April 2015) (DSITI: Brisbane). Available at https://environment.ehp.qld.gov.au/regional-ecosystems/list/?bioregion=7 [cited 15 May 2016]

Shepard C. C., Crain C. M. & Beck M. W. (2011) The Protective Role of Coastal Marshes: A Systematic Review and Meta-analysis. *PLoS ONE* **6**, e27374.

Spalding M. D., Ruffo S., Lacambra C., Meliane I., Hale L. Z., Shepard C. C. & Beck M. W. (2014) The role of ecosystems in coastal protection: Adapting to climate change and coastal hazards. *Ocean Coast. Manage.* **90**, 50-7

Webb, L.J. (1958) Cyclones as an ecological factor in tropical lowland rainforest, North Queensland. *Australian Journal of Botany* 6: 220-228.

Northern Australia Environmental Resources Hub

National Environmental Science Programme

www.nespnorthern.edu.au

This project is supported through funding from the Australian Government's National Environmental Science Programme.

CSIRO

JAMES COOK UNIVERSITY AUSTRALIA