Australia's National
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Mapping land surface temperatures and heat-health vulnerability in Darwin

Jacqui Meyers, Art Langston, Drew Devereux, and Brenda Lin

Australian Government

NORTHERN TERRITORY GOVERNMENT

CITY OF DARWIN

About

This report was delivered as part of the work of the Darwin Living Lab. The Darwin Living Lab was established to foster improvements in the liveability, sustainability and resilience of the city. The Darwin Living Lab is an initiative under the Darwin City Deal and is a 10-year collaboration between CSIRO and the partners of the Darwin City Deal: Australian Government, Northern Territory Government and the City of Darwin. The City Deal was signed by the Prime Minister of Australia, Chief Minister of the Northern Territory and Lord Mayor of the City of Darwin in November 2018.

More information and contacts available at: https://research.csiro.au/darwinlivinglab/

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We acknowledge the Traditional Owners of the greater Darwin region, the Larrakia people, and recognise their culture, history and connection to this land and water. We pay our respects to their Elders past, present and emerging.

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Acronyms and glossary

ABS	Australian Bureau of Statistics
ABS 2016 Census	Australian Bureau of Statistics 2016 Census of Population and Housing
BOM	Bureau of Meteorology
CBD	Central Business District
CDU	Charles Darwin University
CSIRO	Commonwealth Scientific and Industrial Research Organisation
Grass	Native and introduced grasses and pasture
JCU	James Cook University
LGA	Local Government Area
LST	Land surface temperatures
LiDAR	Light Detection and Ranging; a survey method that measures distance to a target using laser light
Mesh Block	The smallest geographical unit for which ABS Census data are available. The majority of populated Mesh Blocks contain between 30 to 60 dwellings but if there are more dwellings in a large building or complex, these are grouped into one Mesh Block (ABS, 2016a)
NDVI	Normalized Difference Vegetation Index
NHVI	Neighbourhood Heat-Health Vulnerability Index where a Mesh Block is defined as a 'neighbourhood'
Savanna woodland	A mixed woodland-grassland ecosystem in which trees have an open canopy that does not close, allowing sufficient light to reach the ground to support an unbroken grassy herbaceous layer
TIRS	Thermal Infrared Sensor on-board the Landsat 8 satellite
TPZ	Town Planning Zones
UCL	Urban Centre/Locality; an ABS area of concentrated urban development with populations of 200 people or more that are primarily identified using objective dwelling and population density criteria using data from the 2016 Census
Greater Urban Area	An area that incorporates the ABS Darwin Urban Centre/Locality and Darwin and Palmerston Local Government Areas
UNSW	University of New South Wales

Executive summary

High temperatures can have multiple impacts on air and water quality, resource use and human health. Prolonged exposure to high temperatures and high humidity can increase the risk of poor health in sensitive populations. Darwin's climate is projected to become warmer in the future, providing a challenge to improve thermal comfort in the city.

The Darwin City Deal aims to transform Darwin into a best-practice example of tropical urban living. A key commitment of this deal is to cool and green the city to improve its liveability. This report assists with that goal by providing information to the Northern Territory Government, the City of Darwin and the City of Palmerston to support action to reduce urban heat. It is a companion to the CSIRO report '*Developing a Darwin Heat Mitigation Strategy: A resource towards strategy development for the Northern Territory Government and City of Darwin'* (Lin et al., 2020), which provides a compilation of strategies and options to reduce urban heat in Darwin

Specifically, we map seasonal land surface temperatures in Darwin and model patterns of heat distribution against several built and natural urban features. We show that land surface temperatures vary with different types of surface cover, the type and seasonality of vegetation, the presence of water, and distance from the coast. We also provide maps of neighbourhood heat-health vulnerability based on data from the 2016 ABS Census of Population and Housing. Together, these maps help to build the evidence base to guide climate adaptation planning in Darwin.

Key findings

Land surface temperature 'hot spots'

Identifying features associated with thermal 'hot spots' can support mitigation plans for counteracting overheating in urban areas. Hotter areas typically have a high proportion of buildings and paved surfaces and have few trees, which is common in commercial and industrial areas. Built infrastructure tends to have high heat holding capacity, storing heat during the day and releasing it slowly at night (known as the heat-island effect). Hot surface temperatures can also be found where there is extensive bare ground or sparse dry vegetation, but unlike areas with significant built infrastructure, these areas cool down quickly at night. They are also relatively cooler in wetter periods when the groundcover is green and there is higher soil moisture.

Areas with hotter surface temperatures include:

- Industrial areas (e.g. Winnellie, Pinelands, Yarrawonga) that have a high proportion of buildings and paving.
- Major roads such as the Stuart Highway and intersections that have little shade.
- Wharf/transport/storage/handling hubs with little shade and large areas of paving (e.g. East Arm Wharf).
- New housing developments (e.g. Muirhead, Johnston, Farrar), with extensive areas of bare ground, roofs and paving, and few trees, leafy parks or irrigated gardens. These areas will become cooler over time as trees and gardens become established.
- High-density accommodation with little green vegetation (e.g. Larrakeyah and Robertson Barracks).
- Sport, transport, or agricultural sites with sparse dry grass and exposed ground (e.g. Darwin Airport, Hidden Valley Raceway, rural pasture, Darwin Turf Club, unirrigated sports fields). Surface temperatures will be relatively cooler in wetter months when the grass is green and more abundant.
- Rural and construction sites with bare ground that has been cleared or burned.

Land surface temperature 'cool spots'

'Cool spots' are important areas in a city, providing respite from extreme heat in other parts of the city and for the cooling effect they have on nearby hot areas. Areas that are cooler during the day are found where there is water, green vegetation or shade. The coolest vegetation types remain green all year, have denser canopies and grow in wetter areas, for example, mangroves, coastal rainforest and riverine vegetation. Areas with shade cast by buildings, trees or shade structures are also cooler.

Areas with cooler surface temperatures include:

- Wet areas along the coast, rivers, estuaries and lakes.
- Mangroves, coastal rainforest and riverine vegetation that have dense foliage, particularly if it is found in wetter areas.
- Leafy, irrigated public areas such as the Darwin Botanic Gardens.
- Irrigated areas, water features, ocean and lake edges that include irrigated playing fields, marinas, golf courses, wetlands, and sewage settling ponds.
- Residential areas that have green vegetation, tree cover and irrigated gardens (e.g. Stuart Park).
- Areas that are shaded by built structures, particularly if the structures are built from cool materials.

Land surface temperatures and land-use planning

Different land cover types and Town Planning Zones (TPZ) have different mean surface temperature and vegetation cover profiles. Understanding which features typically have higher of lower surface temperatures can assist planners with choosing materials or land cover types that can reduce urban heat. Comparisons of different TPZ showed that 'Industrial' and 'Service Commercial' zones had comparatively little tree cover and were more than 4.5 °C warmer on average than the coolest TPZ 'Conservation'.

Neighbourhood land surface temperatures and urban features

A model was created to determine the contribution that different urban features such as dwelling density, distance from the coast, bare ground, roads and paths, buildings, and tree cover make to land surface temperatures in residential neighbourhoods. We found that there is a 7.5 °C mean land surface temperature difference between the warmest and coolest residential neighbourhoods and that neighbourhoods are cooler when they have more tree cover, less bare ground, roads and paths, and are closer to the coast.

Population vulnerability

The Neighbourhood Heat-Health Vulnerability Index was created to identify areas where more residents may be exposed to high temperatures and have a high risk of heat-related illness and fewer economic resources to invest in adaptation strategies. Based on ABS Census data for 2016, small areas with high heat-health vulnerability were found within the City of Darwin (Ludmilla, Tiwi, Berrima, The Narrow, Fannie Bay, Marrara, Coconut Grove, and Darwin City), the City of Palmerston (Johnston, Gray, Bellamack, and Moulden) and in Litchfield (Holtze). The areas identified exhibited higher median land surface temperatures and had residents living in either low-income households, public housing, Indigenous communities, aged care facilities, or correctional facilities.

Conclusion and potential next steps

This report and the spatial data developed in this project provide resources to support the Northern Territory Government, the City of Darwin and the City of Palmerston in taking actions to mitigate urban heat. The data, maps and analyses prepared in this project contribute to the knowledge base of urban heat and heat-health vulnerability across the Darwin region. The work complements previous findings by researchers who focused on different aspects of urban heat and heat-health vulnerability in Darwin.

1 Introduction

Darwin has a diverse and multicultural population of almost 150,000 people including the Larrakia people who are the traditional owners of the region. Darwin has a wet-dry tropical climate with year-round warm to hot daytime temperatures and high humidity during the wet season. Climate change is projected to increase temperatures (Webb and Hennessy, 2015) exacerbating the risk of heat stress and heat-related illness in the city (Loughnan et al., 2013; Oppermann et al., 2017; Parsons, 2014).

Temperature, humidity, exposure, exertion, and sensitivity are key elements of health that combine to produce different levels of heat-health risk in a population (Oppermann et al., 2017). Developing an understanding of how these elements vary across Darwin is one step towards having the information to manage that risk.

This project contributes to this understanding by providing maps of land surface temperature and potential heat-health vulnerability in Darwin. Using thermal data from satellites to generate maps of land surface temperatures has been a standard method for assessing the geographic distribution of urban heat for more than 20 years in cities around the world (Estoque et al., 2017; Imhoff et al., 2010; Maimaitiyiming et al., 2014) and in Australia (202020 Vision, 2017; Coutts et al., 2016; Deilami et al., 2016; Sharifi et al., 2017).

The Darwin City Deal is a ten year plan to position Darwin as a vibrant and liveable tropical city, supported by a growing population and diverse economy (Australian Government et al., 2018). A key commitment of the Darwin City Deal is to improve liveability by cooling and greening the city.

This report and associated spatial data are deliverables to the Darwin City Deal, providing resources to support the Northern Territory Government, the City of Darwin and the City of Palmerston with mitigating urban heat. This foundational research also provides baseline measurements for evaluating heat mitigation efforts and for developing further research initiatives, for example, the effect of humidity on thermal comfort.

The project brief was to:

1. Generate Landsat 8 land surface temperature estimates for the City of Darwin LGA, ideally for both wet and dry seasons, to build an understanding of how heat is distributed across the LGA.
2. Use data from the Australian Bureau of Statistics (ABS) and other relevant sources to characterise the sociodemographic and individual risk factors for health impacts during urban heat, as well as the role of 'place', including housing, urban form and social-ecological context.
3. Develop a spatially-explicit model of integrated datasets and map patterns of vulnerability to urban heat across the City of Darwin.

This report is divided into six sections:

- Section 1**:** Introduction to the report
- Section 2**:** Summary of Darwin's climate, urban heat and heat sensitivity in the population
- Section 3**:** Methods used to develop maps of land surface temperatures and neighbourhood heat-health vulnerability
- Section 4**:** Maps of land surface temperatures and a summary of findings
- Section 5**:** Maps of neighbourhood heat-health vulnerability and a summary of findings
- Section 6: Summary and conclusions

2 Background

2.1 The Darwin climate

Darwin's tropical savanna climate has distinct wet and dry seasons and year-round warm to hot temperatures (Every et al., 2020). In the wet season high temperatures combined with high humidity can make conditions feel very uncomfortable and it can be difficult to get a good night's sleep when overnight temperatures remain warm. In contrast, the dry season has lower humidity and cooler overnight temperatures, often below 20 °C, making conditions more comfortable for sleeping at night.

The wet season begins with the early storm period in October or November. This period is often referred to as the 'build-up' and is characterised by an increase in atmospheric humidity and patchy convective storms (Braithwaite, 1988). This is followed by the onset of the monsoon period in December or January, but most rain falls in February and March (Figure 1). Occasional storms continue into the transition period between the wet and dry seasons in April and May. This is followed by the dry season when temperatures are slightly cooler and soil and atmospheric moisture levels are lower.

Indigenous cultural knowledge has recognised seven seasons for the area that includes Darwin, Cox Peninsula and Gunn Point. Members of the Gulumoerrgin (Larrakia) language group and CSIRO developed a calendar representing seasonal ecological knowledge, identifying Balnba (rainy season), Dalay (monsoon season), Mayilema (speargrass, Magpie Goose egg and knock 'em down season), Damibila (Barramundi and bush fruit time), Dinidjanggama (heavy dew time), Gurrulwa (big wind time) and Dalirrgang (build-up) (Williams et al., 2012).

Over the last 20 years, mean monthly maximum temperatures in Darwin only ranged between 31 °C in June and 33.9 °C in October while minimum temperatures varied between 19.3 °C in July and 25.3 °C in November (BOM, 2019a) (Figure 1). Mean annual rainfall was 1731 mm with almost all rain falling during the wet season.

Cyclones have caused far-reaching damage and loss of life in Darwin over the years, but impacts have lessened since the introduction of cyclone building codes (Miller, 2014). In March 2018, Tropical Cyclone Marcus hit Darwin and felled thousands of trees, resulting in damage to buildings and cars, but no lives were lost (BOM, 2019b).

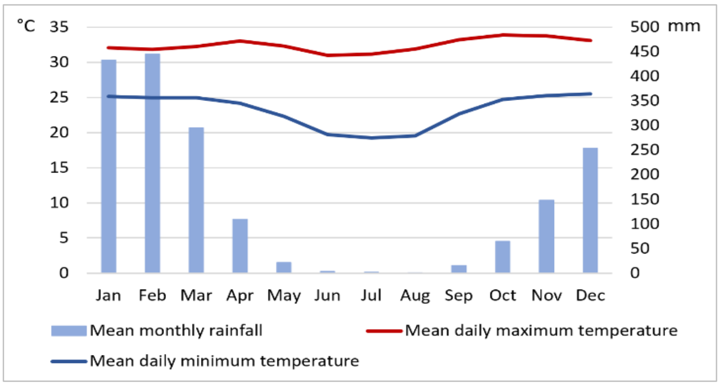


Figure 1. 20-year mean monthly rainfall and temperature data for Darwin Airport (1999–2018).

Data source: BOM Climate Data Online (BOM, 2019a).

Climate change is projected to increase the number of days above 35 °C, from an average of 11 days per year during the period 1981–2010, to an average of 43 days per year by 2030 (under a moderate emissions scenario) (Webb and Hennessy, 2015). In 2019, Darwin exceeded this number with 45 days above 35 °C, including a record of 11 days in a row in December (BOM, 2020). December 2019 also had the highest daily minimum (30.2 °C) ever recorded at Darwin Airport. A rise in the number of very high temperature days in the future has the potential to increase the risk of heat-related illness and death (Loughnan et al., 2013; Parsons, 2014), presenting a challenge to improve thermal comfort in Darwin.

Climate change is also projected to bring more intense rainfall events and fewer, but more intense tropical cyclones, but at this stage the magnitude of these changes cannot be predicted with high confidence (Webb and Hennessy, 2015).

2.2 Urban heat islands

Rural areas have an abundance of vegetation, relatively few built structures, and cool down quickly at night (Oke, 1981; 1987). By contrast, cities have high concentrations of buildings and paved surfaces that absorb solar radiation and heat from vehicles, industries and air-conditioning systems during the day and release this stored heat slowly back into the atmosphere at night (Rizwan et al., 2008; U.S. Environmental Protection Agency, 2008). Another major reason is the lower level of evapotranspiration from vegetation in urban areas (Kumar et al., 2017).

This night-time phenomenon is known as the Urban Heat Island (UHI) effect because in thermal mapping, urban temperatures appear like a warm island surrounded by cooler night-time temperatures in rural areas. Urban heat islands are found in most cities around the world (Arnfield, 2003). They can create problems for human health when higher urban temperatures lower thermal comfort, reduce water quality, and lower air quality which can exacerbate respiratory problems (Akbari and Konopacki, 2005; Mullins, 2018). Higher urban temperatures also increase the need for air-conditioning.

The choice of building materials can influence how heat is stored (heat capacity), reflected (albedo) and emitted (emissivity) because different building materials have different thermal properties. Cities tend to have lots of building materials that have low albedo, low emissivity, and high heat capacity. The layout and design of buildings and streets also contributes to urban heat by influencing whether hot air becomes trapped during the day, hindering its release back into the cooler atmosphere at night (Arnfield, 2003).

2.3 Surface urban heat islands

In the absence of a dense network of meteorological stations to measure air temperature across an entire city, satellite thermal infrared imagery is commonly used to estimate land surface temperature as a proxy for urban heat. This is an effective way to assess thermal patterns across a wide area and to monitor changes over time, especially when it is integrated with other locally sourced information. The use of this technique has been widely adopted for assessing urban heat in many cities around the world (Estoque et al., 2017; Imhoff et al., 2010; Maimaitiyiming et al., 2014), including in Australia (Coutts et al., 2016; Deilami et al., 2016; Sidiqui et al., 2016), and in Darwin (202020 Vision, 2017; Devereux and Caccetta, 2017).

The term 'urban heat island' refers to air temperature measurements, but when surface temperature is measured, the term 'surface urban heat island' is used. While there is not always a direct relationship between air and surface temperatures, the presence of a surface urban heat island indicates that an urban heat island phenomenon is occurring. In general, areas with higher near-ground air temperature tend to have higher land surface temperatures and vice versa (Coutts et al., 2016). For example, areas of irrigated greenspace typically have cooler surface and air temperatures while large areas of paving have warmer surface and air temperatures (Roth et al., 1989; U.S. Environmental Protection Agency, 2008).

2.4 Extreme heat and human health

Optimal human health and physiological functioning relies on the maintenance of an internal body temperature between 36.5 ˚C and 37.4 ˚C (Parsons, 2014). Physiological and behavioural responses help to maintain body temperature within this range, but a shift in core temperature beyond this range can result in serious illness and in extreme cases, death (Health and Safety Professionals Alliance, 2012; Loughnan et al., 2013). In hot conditions, the body maintains its core temperature by shedding heat through dilated blood vessels in the skin and by sweating (Hanna and Tait, 2015). Sweating is an effective heat loss mechanism that relies on evaporation from the skin. However, on hot, humid days when there is little wind, sweat evaporates more slowly, making it difficult to maintain core body temperature (Oppermann et al., 2017; Sherwood, 2018). Dressing in light clothing, keeping hydrated, using air-conditioning, and adopting behavioural strategies such as seeking refuge in cool places, can help to reduce heat exposure and the associated risk of heat-related illness (Bouchama et al., 2007; Vandentorren et al., 2006).

Despite acclimatisation to the local climate, heat-related illness and death is a regular occurrence in Darwin (Bambrick H et al., 2008; Loughnan et al., 2013; Webb et al., 2014). A study of the effects of temperature and humidity on hospital admission rates in Darwin over an 18 year period indicated that there were higher admission rates when hot days were preceded by high night-time humidity (Goldie et al., 2015). In another study, a model of weather conditions and daily anomalies in hospital admissions in Darwin indicated that an increase of 1 °C in daily maximum temperature could increase hospital admissions by 7.9% (Haddad et al., 2020). Significantly, when temperatures were higher than 32 °C and humidity was more than 80%, an increase in daily maximum temperature by 1 °C could raises the number of hospital admissions by 263%.

Certain groups in the community are more sensitive to prolonged heat exposure. The ability to shed heat can be compromised in people who are elderly (Josseran et al., 2010; Kovats et al., 2004), are very young (Kovats et al., 2004), lack mobility (Vandentorren et al., 2006), or are unable to adequately care for themselves (Bouchama et al., 2007; Kilbourne et al., 1982). Excessive heat can also exacerbate some mental and physical health conditions (Khalaj et al., 2010; Larrieu et al., 2008) including renal (Hansen et al., 2008; Nitschke et al., 2007) and cardiovascular (Khalaj et al., 2010; Loughnan et al., 2008) disease, conditions that are more prevalent among the Indigenous population (Bauert, 2005; Penm, 2008; Webb et al., 2014).

When temperature and humidity conditions rise above the range for comfort, health and performance problems can arise leading to a greater use of air-conditioners or greater exposure for people who work or spend time outdoors. Exposure to high temperatures are therefore a health hazard for people who are physically active or work outdoors, or who work indoors in hot environments (Hanna et al., 2011; Zander et al., 2015).

Other groups, particularly those in low socioeconomic circumstances are more likely to be exposed to high temperature conditions for prolonged periods if costs restrict their ability to cool their homes or invest in other adaptation strategies (Farbotko and Waitt, 2011; Nance, 2017). In particular, heat exposure may be exacerbated if people are homeless, do not have adequate shelter, or live in substandard housing (ACOSS, 2011; Balbus and Malina, 2009).

In summary, people may be more exposed to high temperatures or more vulnerable to its effects through a combination of socioeconomic, health, age and activity related factors. Identifying areas with high heat exposure and populations with high heat-health risk can be useful for targeting actions to reduce urban heat in areas of need (Bao et al., 2015).

3 Rationale and methods

3.1 Estimating land surface temperatures

3.1.1 Advantages and disadvantages of satellite remote sensing

Satellite remote sensing is a useful tool for characterising land use, land cover and land surface temperatures. It has been used to estimate land surface temperatures in many cities around the world, offering a method to study thermal environments at various spatial (local to global) and temporal (diurnal, seasonal, and interannual) scales (Zhou et al., 2019). It is a simple and cost-effective method for capturing data across a broad area at a single point in time and provides repeated coverage whenever the satellite passes overhead which is useful for assessing changes in dynamic systems over time. The data can be processed and analysed quickly, and is easily integrated into a Geographic Information System where it can be used for a variety of purposes (Patino and Duque, 2013; Wentz et al., 2014).

However, there are some limitations of the approach that need to be considered in how the results are applied and analysed. Although surface temperature will not be the same as the air temperature at any one location, there is a relationship between the two measurements. Land surface temperatures are most similar to near-ground air temperatures early in the morning, but throughout the day surface temperatures become more variable than air temperatures and are faster to respond to sudden changes such as shade from clouds passing overhead (Good, 2016). There can also be a disconnect between air and surface temperatures when it is windy (Coutts et al., 2016) and between rooftop temperatures of tall buildings and air temperatures measured at street level (Roth et al., 1989).

The thermal data provides a snapshot of surface temperatures at the time the satellite passes overhead; however, it cannot be assumed that the same temperature patterns will be observed across the city at other times of the day (Voogt and Oke, 1997; 2003). For example, shadows cast from tall buildings, trees and other objects shift across the course of the day and have different lengths depending on the time of year.

Another limitation of using this approach is that satellites provide a birds-eye view of the city, collecting data for rooftops, roads and the tops of tree canopies, but do not capture ground temperatures beneath canopies, or vertical surfaces such as the sides of buildings, or on steep slopes. Also, land surface temperatures may not be accurate for surfaces with very low emissivity, such as highly reflective rooftops. Irrespective of these limitations, land surface temperature measurements are useful for assessing patterns of urban heat across broad areas.

3.1.2 Creating seasonal land surface temperature maps

The Landsat 8 satellite passes over Darwin every 16 days at approximately 10:20 a.m. with a Thermal Infrared Sensor (TIRS) on-board. The TIRS data used in this study was provided by the United States Geological Survey (USGS, 2019) at a spatial scale of 30 metres (downscaled from 100 metres prior to supply). The data are therefore average estimates of the observations within each 30 metre square.

All images of Darwin between April 2018 (i.e. after Tropical Cyclone Marcus) and August 2019 were inspected. Only images that were cloud and smoke free across the urban area of Darwin were suitable for inclusion. On this basis, only ten images, between April and August were suitable for use in this project (Table 1).

For each of the ten dates, two adjoining Landsat 8 images were combined to create a single image that covered the geographic extent of Darwin. All spatial mapping in this project was performed using the geospatial tool ArcGIS 10.5 (ESRI, 2017). The TIRS sensor on the Landsat 8 satellite collects two thermal bands (Bands 10 and 11). Design flaws in the satellite sensors have resulted in systematic errors in the values recorded by these sensors and the errors are variable depending on the composition of the land being sensed. While mathematical corrections reduce the error in both bands, better results were achieved using the single Band 10 to calculate land surface temperatures for this project. Land surface temperature was estimated following the method of Jimenez-Munoz and Sobrino (Jimenez-Munoz et al., 2009; Jimenez-Munoz and Sobrino, 2003) with modifications appropriate for Landsat 8 (Buck, 1981; Yu et al., 2014). Values for total atmospheric water vapour content were calculated using 9 a.m. air temperature and relative humidity measurements from Darwin Airport (Table 1).

Table 1. Landsat 8 images collected at 10:20 a.m. and corresponding 9 a.m. and daily weather conditions at Darwin Airport (Station ID: 014015).

Season	*Date of Landsat 8 Imagery collected*	*9 a.m. air temp. (°C)*	*9 a.m. relative humidity (%)*	*9 a.m. tide*	*Daily min. air temp (°C)*	*Daily max. air temp. (°C)*	*7-day rainfall (mm)*
Transition	17 Apr 2018	29.1	71	Low	25.0	35.1	17.8
	6 May 2019	26.0	59	High	23.4	32.6	26.4
	19 May 2018	22.7	52	High	19.4	30.9	0
	22 May 2019	27.0	55	High	23.2	33.3	5.4
Dry	4 Jun 2018	21.6	42	High	18.7	30.7	0
	20 Jun 2018	26.3	26	High	20.7	33.4	0
	23 Jun 2019	20.4	31	Flow	15.7	30.1	0
	9 Jul 2019	24.9	71	Flow	18.4	32.3	0
	22 Jul 2018	24.1	28	Flow	17.8	33.0	0
	7 Aug 2019	25.1	21	Flow	21.2	34.0	0

Calculating land surface temperature requires values of land surface emissivity. These were estimated using an approach based on the Normalized Difference Vegetation Index (NDVI) which is a measure of the vigour of live green vegetation (Lo and Quattrochi, 2003; Sobrino and Raissouni, 2000; Yu et al., 2014). This approach calculates the fractional vegetation cover for each 30 metre square, which in turn is used to determine an emissivity value that is intermediate between vegetation and non-vegetation emissivity values. A value at the lower threshold is treated as containing no vegetation and may consist of bare soil, asphalt, brick, concrete or other similar surface materials, whereas the upper threshold, set to 0.9863, indicates an abundance of live green vegetation (Yu et al., 2014). To further reduce the systemic error, composite seasonal images were created by overlaying the daily images and deriving the median value within each 30 metre square.

NDVI was examined across the ten dates. As the season became drier between April and August, the vegetation became less green and abundant, particularly in rural areas, as the grasses dried, the deciduous trees and shrubs lost their leaves, and more ground became exposed (Figure 3). There is a well-established relationship between NDVI and LST as vegetation vigour has an important influence on land surface temperature. In line with the drying of the vegetation between April and August, the surface temperatures also shifted across the dry season, particularly in rural areas. As a result of this finding, two composite LST images were created, one for the seasonal transition period (April–May) and one the dry season (June–August).

3.2 Land surface temperatures of urban features

3.2.1 Land surface temperature and land cover type

Assessing the relationship between land surface temperatures and land cover/vegetation type requires appropriate spatial data. Data on different vegetation types were available for rural areas around Darwin, but not for all urban areas. In response, a classification scheme of broad vegetation and land cover types for Darwin was developed by CSIRO for this project.

The classification was developed at an alignment and spatial resolution of 30 metres to match the resolution of the land surface temperature data. The data sets used to develop the land cover classification were:

Layer 1: Remnant vegetation survey: Darwin to Palmerston region (Brock, 1995)
Layer 2: Catchment scale land use of Australia – 2014 update (DAWR, 2014)
Layer 3: Landsat 8 Bands 5, 6 and 7 for imagery dated 6 May 2019 (USGS, 2019)
Layer 4: Digital Elevation Model of Australia derived from LiDAR 5 Metre Grid (Geoscience Australia, 2015)

The extent of existing remnant vegetation was determined from data in Layers 1 and 2. For the remaining areas, broad cover classes were developed by running an unsupervised Iso Cluster Classification on the Landsat 8 (Layer 3) spectral signals which finds spectrally similar clusters in the multiband image. Based on the spectral signals of known class types and visual inspection, the clusters were classified into broad land cover classes, as follows: Water, Mixed Woodland, Beach and Mudflats (coast), Hard Surface (inland), Bare Ground, Dry Grass, Green Grass, Roof and Moderate Trees, Roof and Sparse Trees, and Roof Dominated. The three classes with roofs and trees were differentiated into the three new classes based on their relative proportions within each 30 metre square. Mixed and unassigned classes were reclassified based on spatial relationships between classes and topographic location using the DEM data (Layer 4).

Trained from the Landsat 8 spectral signals (Layer 3) for vegetation classes within the extant remnant vegetation (Layer 1) (i.e. *Melaleuca*, *Eucalyptus*, *Pandanus*, and Riparian) (Layer 1), a Maximum Likelihood Classification was run and the results were applied to the Mixed Woodland class (previously identified) within the urban extent. The final classifications were combined with the remnant vegetation layer (Layer 1) to form the land cover classification map, and summary statistics were calculated by land cover class.

3.2.2 Land surface temperature and Town Planning Zones

To assess the relationship between surface temperatures and land cover, the map of dry season land surface temperature was overlaid with a map of Town Planning Zones for the region (NTG, 2019). This data was made available with permission from the Northern Territory Government for use in this project. Median LST was extracted for each Town Planning Zone class.

3.2.3 'Potential' planting areas to reduce high land surface temperatures

Some areas of bare ground or sparse dry groundcover could be appropriate for planting trees or other evergreen vegetation to reduce high surface temperatures. Locating appropriate spots requires knowledge of where it is hot and where there is bare ground. Planting trees and shrubs would not be appropriate, for example, in areas where they would create a safety hazard, such as at the airport.

The map of 'potential' planting areas to ameliorate high surface temperatures was developed using two data sets:

Layer 1: Dry season land surface temperature developed as part of this project

Layer 2: Surface Cover (*GeoVision™ Geoscape Surface Cover 2019 2 metre grid*) (Pitney Bowes, 2019) made available with permission from the City of Darwin for use in this project. The surface cover classes are: Bare Ground, Roads and Paths, Grass, Trees, Unspecified Vegetation, Built-Up Areas, Water, Buildings, Shadow, and Swimming Pool.

The map of 'potential' planting locations was developed by showing LST (Layer 1) in areas that coincide with areas of grass or bare ground (Layer 2).

3.2.4 Modelling land surface temperatures in residential areas

A model was developed to assess the contribution that some natural and built urban features make to LST in residential neighbourhoods. Neighbourhoods were defined as ABS 2016 Mesh Blocks (ABS, 2016a) classified as 'Residential' (n=1097) within the Greater Urban Area (Figure 2). Most Mesh Blocks contain between 30 and 60 dwellings (ABS, 2016a). Data aggregated up to Mesh Block scale provides insights into the contribution that different features within that Mesh Block make to mean surface temperature.

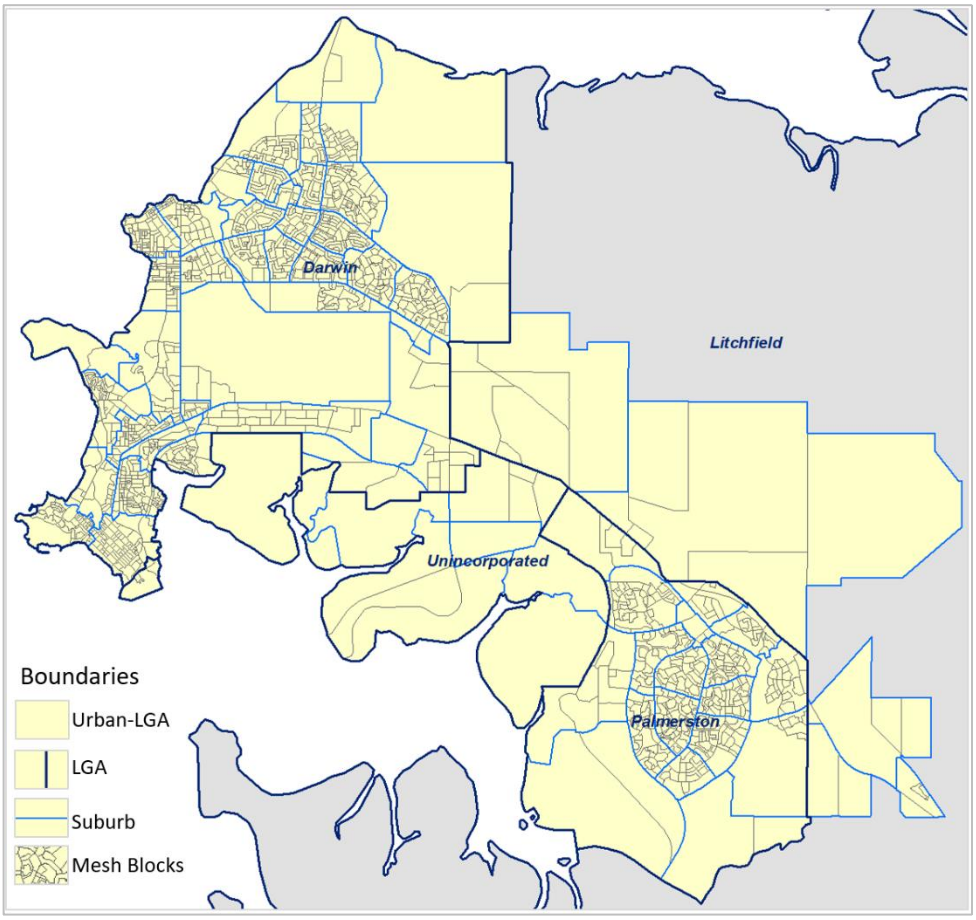


Figure 2. Darwin Area showing the ABS boundaries referred to in this document.
Boundaries: ABS (ABS, 2018).

For each residential Mesh Block, median LST was calculated and expressed as degrees Celsius above the coolest residential Mesh Block. A best fit model multiple linear model was created for LST and features that have been found to contribute to LST in similar studies, including:

- Gross dwelling density, calculated from the area and total number of dwellings in each Mesh Block (ABS, 2016a)
- Distance from the coast, calculated from the centroid of each Mesh Block within the software package ArcGIS 10.5 (ESRI, 2017)

- Percentage of different surface cover types; 'Bare ground', 'Trees', 'Roads and Paths', 'Buildings', 'Impervious Cover' (buildings, roads and paths) based on data in the product *GeoVision™ Geoscape Surface Cover 2019 2 metre grid* (Pitney Bowes, 2019) made available with permission by the City of Darwin for use in this project

The amount of grass cover was not included as a factor as the data does not differentiate irrigated from unirrigated grass, a factor that has been found to be an important determinant of LST. Correlations between the factors were examined and multiple linear regression analyses was applied to develop a 'best-fit' statistically significant model.

3.3 Neighbourhood Heat-Health Vulnerability Index

A population's risk of poor health outcomes from prolonged exposure to high temperatures is dependent on a number of factors including the level of exposure, the health status of the population and the demographic structure of the population (Loughnan et al., 2013). All three aspects were included in a Neighbourhood Heat-Health Vulnerability Index (NHVI) that was created to help identify areas where there are more residents with a higher risk of heat-related illness, have fewer economic resources to cool their homes or invest in adaptation strategies, and are exposed to higher surface temperatures.

Census data can be used to build community profiles about the demographic and socioeconomic makeup of the community and the type of dwelling that people are living in at the time of the Census. The Census is a rich source of data that is updated every five years. Drawbacks in its use, however, are that community profiles may change between Census dates, people may have been missed from the Census either by choice, or if they were travelling or difficult to contact (ABS, 2011). As the number of itinerant or homeless people may be underrepresented in the Census, the NHVI results in this report provide a foundation upon which local knowledge can be added to ensure that heat mitigation actions are appropriately targeted to improve conditions for Darwin's vulnerable residents.

The NHVI is mapped at the ABS Mesh Block scale, which is the smallest area for which Census data are available (ABS, 2016a). Most residential Mesh Blocks contain between 30 and 60 dwellings (ABS, 2016a). Aggregation of data to the Mesh Block level maintains confidentiality of individuals and households. The NHVI was created for all Mesh Blocks within the Darwin Greater Urban Area (see Figure 2 for boundaries). The size of Mesh Blocks does vary but are relatively consistent within urban areas.

Based on a literature review of heat-health risk factors (Section 2.4) and of vulnerability indices developed for other cities (Bao et al., 2015; Reid et al., 2009; Rinner et al., 2010; Wolf et al., 2015), the following ABS 2016 Census variables (ABS, 2016b) were used to create the index:

- Heat-health risk: people who are 'elderly' (65 years or older); 'very young' (under 5 years old); 'need assistance with core activities' (self-care, mobility or communication); or who identify as 'Aboriginal and Torres Strait Islander'.
- Economic resources available to a household: people who live in 'public housing'; or who live in 'low-income households'. Low-income households are often defined as those in the lowest 20% or 25% of income (ABS, 2017; ACOSS, 2011). The modified OECD equivalence scale is used by the ABS to reflect the economic resources available to a standardised household (ABS, 2017) and is adopted in this project. In this measure, the amount of disposable household income is adjusted for the number of people living in a household and the age of the occupants. Based on the lowest 20–25% grouping, an equivalised income below $800 per week is defined as low-income in Darwin, which represents the lowest 24% of household incomes at the time of the Census in August 2016.

The number of people in each Mesh Block who satisfy each of these criteria were extracted using the ABS tool TableBuilder. Two factors were found to be highly correlated; the number of ‘elderly’ people and those who ‘need assistance with core activities’ ($p=0.75$), and the latter was dropped from further analyses.

To estimate potential exposure to higher temperatures, median dry season LST was calculated for each Mesh Block. While Mean Mesh Block LST is a coarse measure, it is indicative of relative exposure between Mesh Blocks. Median LST was calculated rather than mean as it removes bias associated with extreme values which may occur when there are mixed signals in the satellite imagery close to the coast.

The NHVI was calculated by first summing the number of people within each Mesh Block who satisfy the criteria for each of the five risk factors. This represents ‘units of risk’. These values were then ranked and scaled from the Mesh Block with the highest (100) to the lowest (0) risk. The data were ranked because there is no a priori knowledge of the relative importance of an individual count, whereas raw counts would infer that a linear relationship existed. Ranking allows for a simple priority sorting. Next, the median land surface temperatures of Mesh Blocks were ranked and scaled to create a heat exposure score from the hottest (100) to the coolest (0) Mesh Block. Again, ranks were used because there is no a priori relationship between LST values and the relative threat individual values generate. The ranked and scaled ‘units of risk’ and ‘median LST’ were multiplied and the product was ranked and scaled to create a neighbourhood heat-health vulnerability score, from the Mesh Blocks with the highest (100) to the lowest (0) vulnerability.

4 Patterns of land surface temperature

4.1 Seasonal vegetation cover and land surface temperatures

Remotely sensed land surface temperature is a measure of the radiative energy emitted from the surfaces of different types of materials, vegetation, soils, paving, roofs, and so on (Arnfield, 2003; Voogt and Oke, 2003). An important factor that influences land surface temperature is seasonal change in vegetation vigour, or how actively plants are growing (Buyantuyev and Wu, 2010; Yuan and Bauer, 2007). Under the same weather conditions, sparse dry grass and bare ground will typically have higher surface temperatures than green grass (Song et al., 2018). This is relevant for the Darwin region where the landscape is dominated by tropical savanna vegetation with an open eucalypt canopy, a shrubby understorey and a grassy ground layer. Water availability, in the contrasting monsoonal wet and dry seasons, is a critical component in this vegetation system (DSEWPC et al., n.d.).

Actively growing green grass has different radiative properties to dry 'cured' grass (Buyantuyev and Wu, 2010; Yuan and Bauer, 2007). Curing is a measure of grass moisture content, or 'greenness', and relates to the percentage of grass material that is dead in the sward (Johnson, 2002). Grass curing is dependent on seasonal conditions such as rainfall and temperature, with levels increasing over the dry season (Johnson, 2002). Curing is also dependent on plant species and land type. Grasses growing on light sandy soils will dry out and cure more rapidly than grasses growing in heavy clay. Annual grass species will dry out and die off earlier in the dry season than most perennials. Fire hazard also increases as grasses cure and moisture content decreases (Johnson, 2002).

Seasonal cycles in leaf fall in deciduous species also has a strong influence on land surface temperatures (Arnfield, 2003; Voogt and Oke, 2003) and on the surface urban heat island effect (Imhoff et al., 2010; Peng et al., 2012). In the Darwin region, the woody vegetation (trees and tall shrubs) is made up of a mix of species from evergreen to deciduous, with intermediate forms such as semi-deciduous (trees that lose a fraction of their leaves during the dry season) and brevideciduous (trees that shed leaves at the start of the dry season followed by immediate leaf flush (Williams et al., 1997; Eamus, 1999). Different species lose their leaves at different times during the dry season, with peak leaf fall in June and July, even in evergreen species, with secondary peaks in August and September (Duff et al., 1997; Williams et al., 1997).

The remotely sensed NDVI was used to test for shifts in vegetation vigour across the seasons. The ten NDVI images between April and August confirmed the seasonal shift in plant activity across the dry season. Two images, one in April and one in August (Figure 3) shows this shift from 'medium green vegetation' to 'sparse green vegetation' in the Darwin region. Note that the NDVI data displayed in Figure 3 has been grouped into broad classes to clearly show this seasonal shift. This shift reflects the changes in grass curing and leaf fall over the dry season, and possibly other factors such as increased burning activities which is common in savanna woodlands in northern Australia (Williams et al., 2002).

There is a clear relationship between vegetation vigour (Figure 3) and corresponding land surface temperatures (Figure 4) for the transition period (Apr–May) and the dry season (Jun-Aug). In rural areas, land surface temperatures are relatively cooler in the transition period when grasses are greener and most deciduous trees and shrubs still have their leaves. In the dry season, grasses are 'curing', more bare ground is exposed, and deciduous vegetation has lost its leaves. By contrast, coastal vegetation remains green and relatively cooler across the seasons (Figure 4).

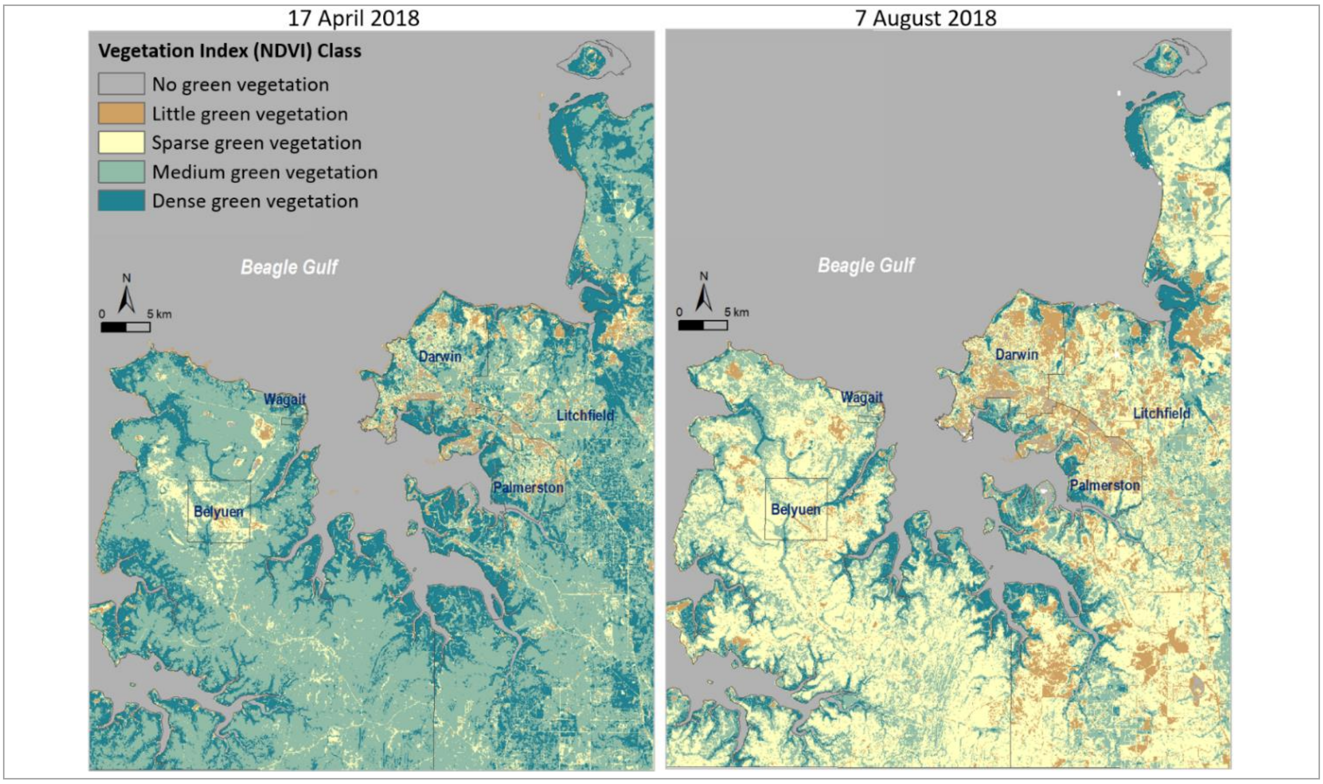


Figure 3. NDVI for (left) 17-April-2018 and (right) 7-August-2018. The data are classed: NDVI <0.1 No green vegetation, NDVI 0.1–0.3 Little green vegetation, NDVI 0.3–0.5 Sparse green vegetation, NDVI 0.5–0.7 Medium green vegetation, NDVI >0.7 Dense green vegetation.

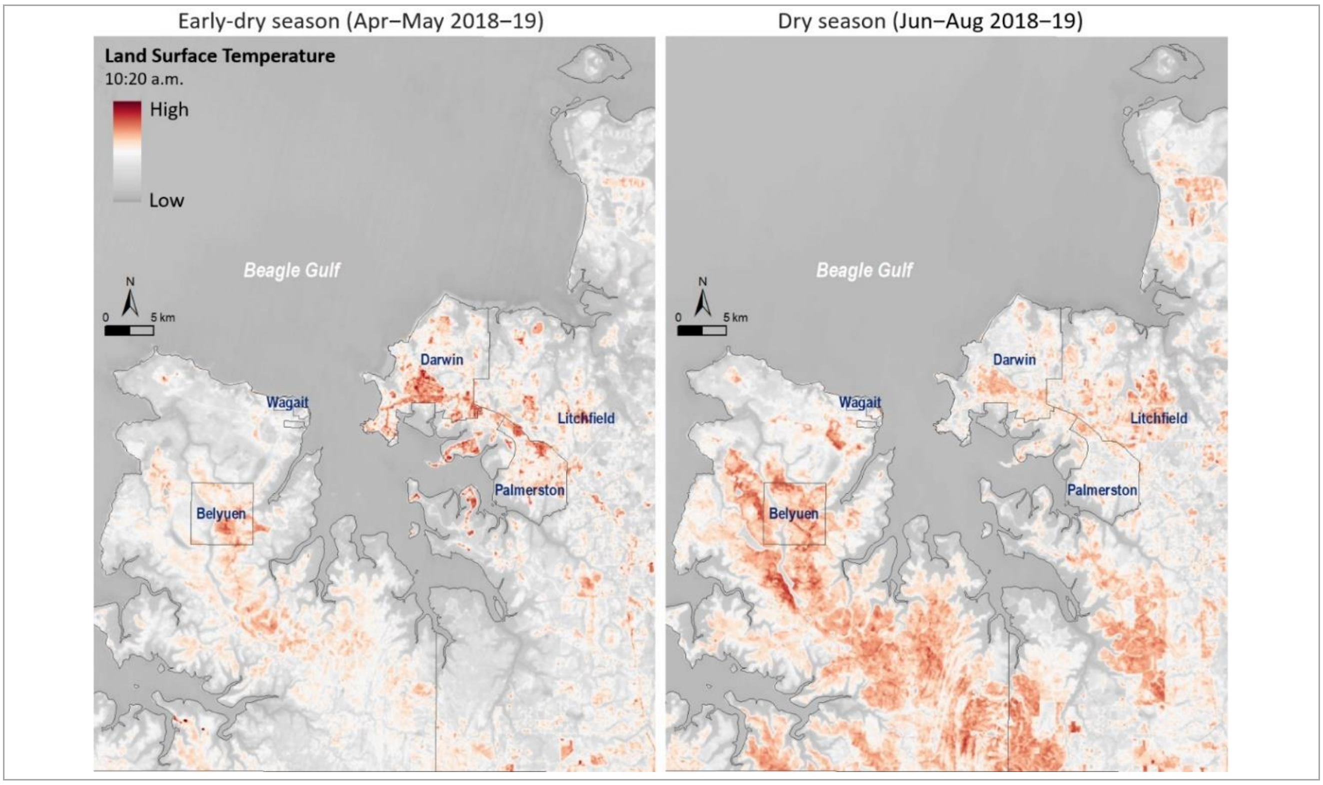


Figure 4. LST for (left) the seasonal transition period (Apr–May) and (right) the dry season (Jun–Aug).

4.2 Greater Urban Area

4.2.1 Dry season land surface temperatures

Unless otherwise specified, results in the remainder of this report are based on the dry season land surface temperature map which is based on Landsat 8 thermal imagery for June, July and August in 2018 and 2019 at 10:20 a.m. (see Table 1 for details). The land surface temperature map (Figure 5) shows that surface temperatures are highest in rural areas and the central strip though Darwin's airport and industrial areas. The coolest temperatures are found in estuaries and vegetation around the coast. Maps, showing greater detail are provided in Appendices for the City of Darwin (Figure 15), Central Darwin (Figure 16), and the City of Palmerston (Figure 18).

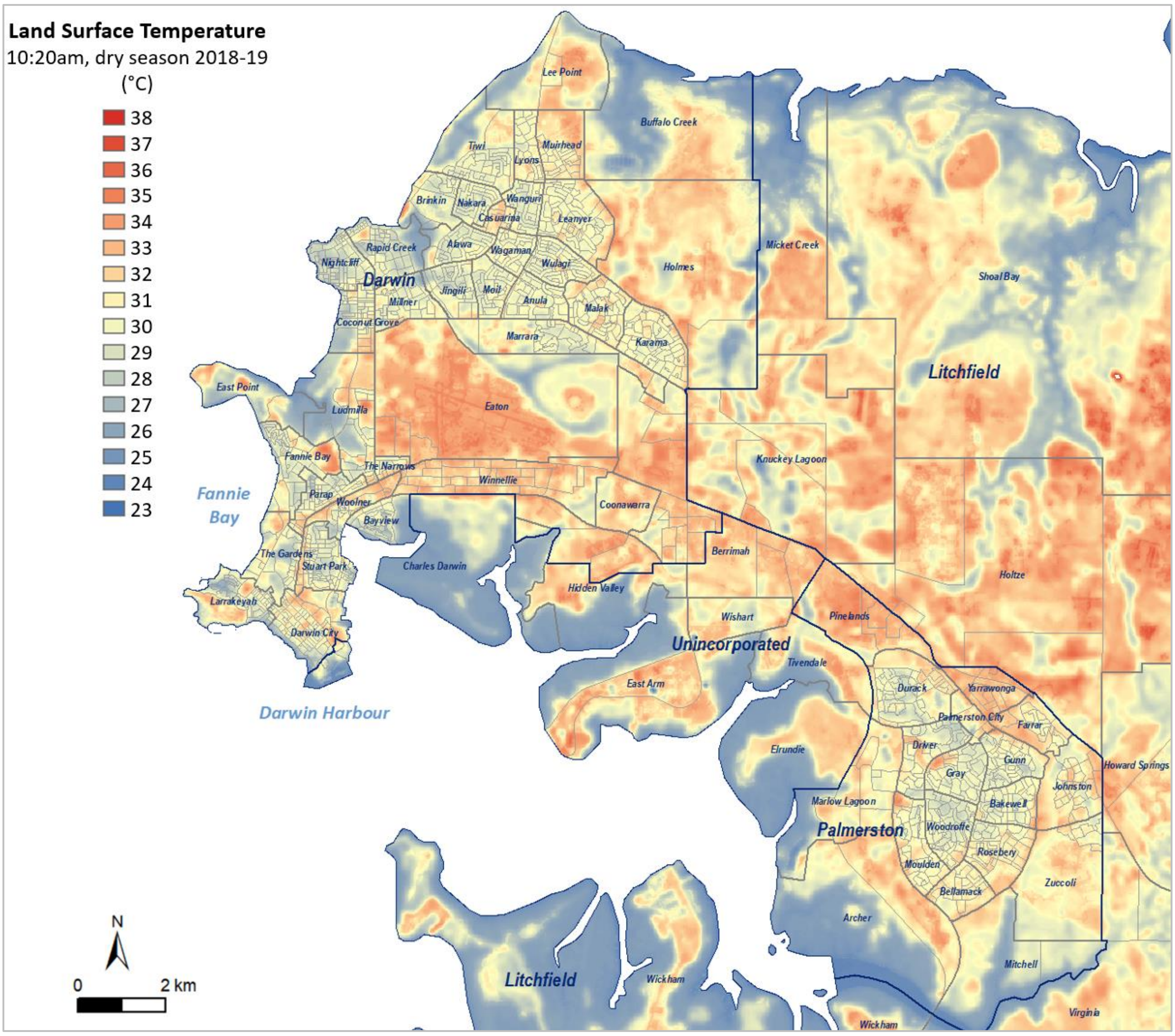


Figure 5. Dry season LST for the Greater Urban Area based on Landsat 8 thermal imagery for Jun–Aug in 2018–19 at 10:20 a.m.

Boundaries: LGA, suburb and Mesh Block (ABS, 2018).

This map of land surface temperatures can be used to explore hot spots and cool spots and the urban features that are associated with these temperatures. Hot spots and cool spots are defined as areas which consistently demonstrate higher or lower land surface temperature, respectively, compared with their surrounding areas (Mavrakou et al., 2018).

4.3 Hot spots

Identifying features associated with thermal 'hot spots' can support mitigation plans for counteracting overheating in urban areas (Mavrakou et al., 2018). Hotter areas typically have a high proportion of buildings and paved surfaces and have few trees, which is common in commercial and industrial areas. Built materials tend to have high heat holding capacity, storing heat during the day and releasing it slowly at night (known as the heat-island effect). Hot surface temperatures can also be found where there is extensive bare ground or sparse dry vegetation, but unlike areas with significant built infrastructure, these areas cool down quickly at night (Rizwan et al., 2008). They are also relatively cooler in wetter periods when the groundcover is green and there is high soil moisture.

Areas with hotter surface temperatures include:

- Industrial areas (e.g. Winnellie, Pinelands, Yarrawonga) that have a high proportion of buildings and paving.
- Major roads such as the Stuart Highway and intersections that have little shade.
- Wharf/transport/storage/handling hubs with little shade and large areas of paving (e.g. East Arm Wharf).
- New housing developments (e.g. Muirhead, Johnston, Farrar), with extensive areas of bare ground, roofs and paving, and few trees, leafy parks or irrigated gardens. These areas will become cooler over time as trees and gardens become established.
- High-density accommodation with little green vegetation (e.g. Larrakeyah and Robertson Barracks).
- Sport, transport, or agricultural sites with sparse dry grass and exposed ground (e.g. Darwin Airport, Hidden Valley Raceway, rural pasture, Darwin Turf Club, unirrigated sports fields). Surface temperatures will be relatively cooler in wetter months when the grass is green and more abundant.
- Rural and construction sites with bare ground that has been cleared or burned.

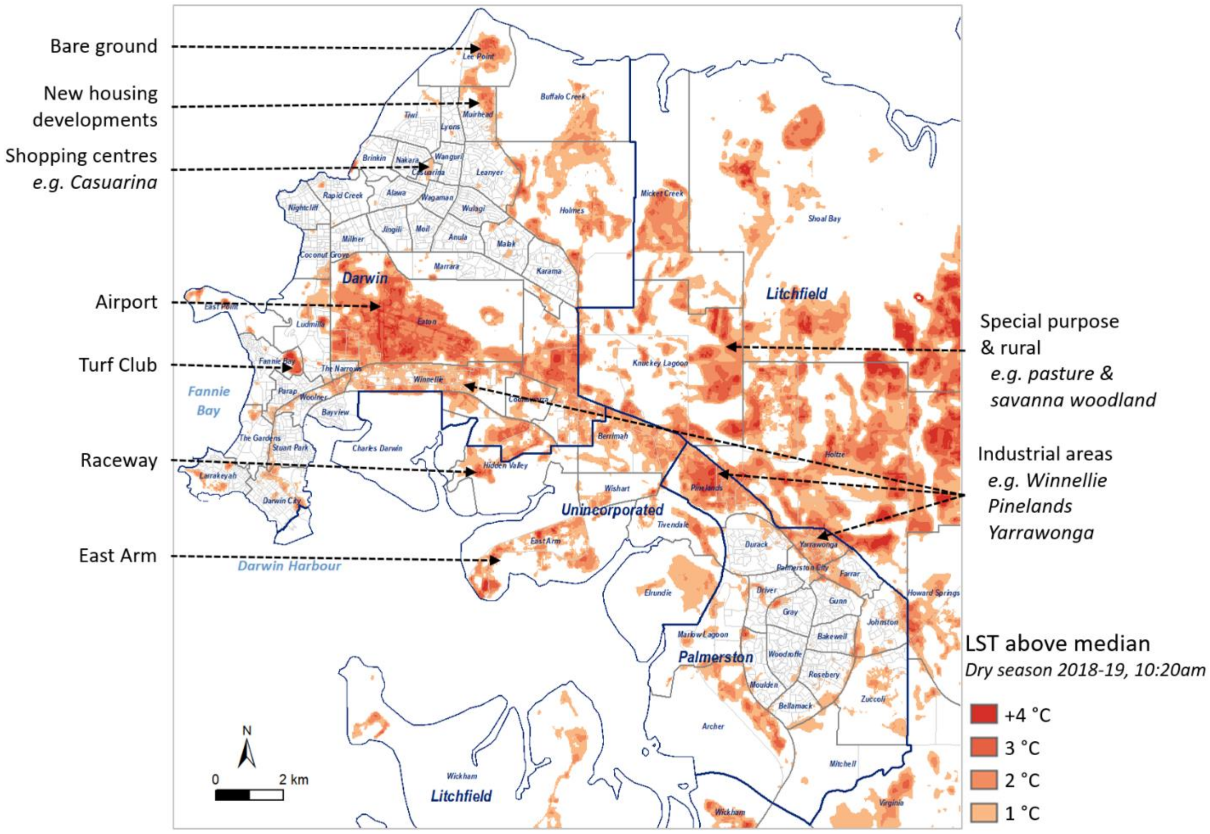


Figure 6. LST 'hot spots' and examples of areas or features with this characteristic.
Boundaries: LGA, suburb and Mesh Blocks (ABS, 2018).

4.4 Cool spots

'Cool spots' are important areas in a city, providing respite from extreme heat in other parts of the city and for the cooling effect they have on nearby hot areas. Areas that are cooler during the day are found where there is water, green vegetation or shade. The coolest vegetation types remain green all year, have denser canopies and grow in wetter areas, for example, mangroves, coastal rainforest and riverine vegetation. Areas with shade cast by buildings, trees or shade structures are also cooler.

Areas with cooler surface temperatures include:

- Wet areas along the coast, rivers, estuaries and lakes.
- Mangroves, coastal rainforest and riverine vegetation that have dense foliage, particularly if it is found in wetter areas.
- Leafy, irrigated public areas such as the Darwin Botanic Gardens.
- Irrigated areas, water features, ocean and lake edges that include irrigated playing fields, marinas, golf courses, wetlands, and sewage settling ponds.
- Residential areas that have green vegetation, tree cover and irrigated gardens (e.g. Stuart Park).
- Areas that are shaded by built structures, particularly if the structures are built from cool materials.

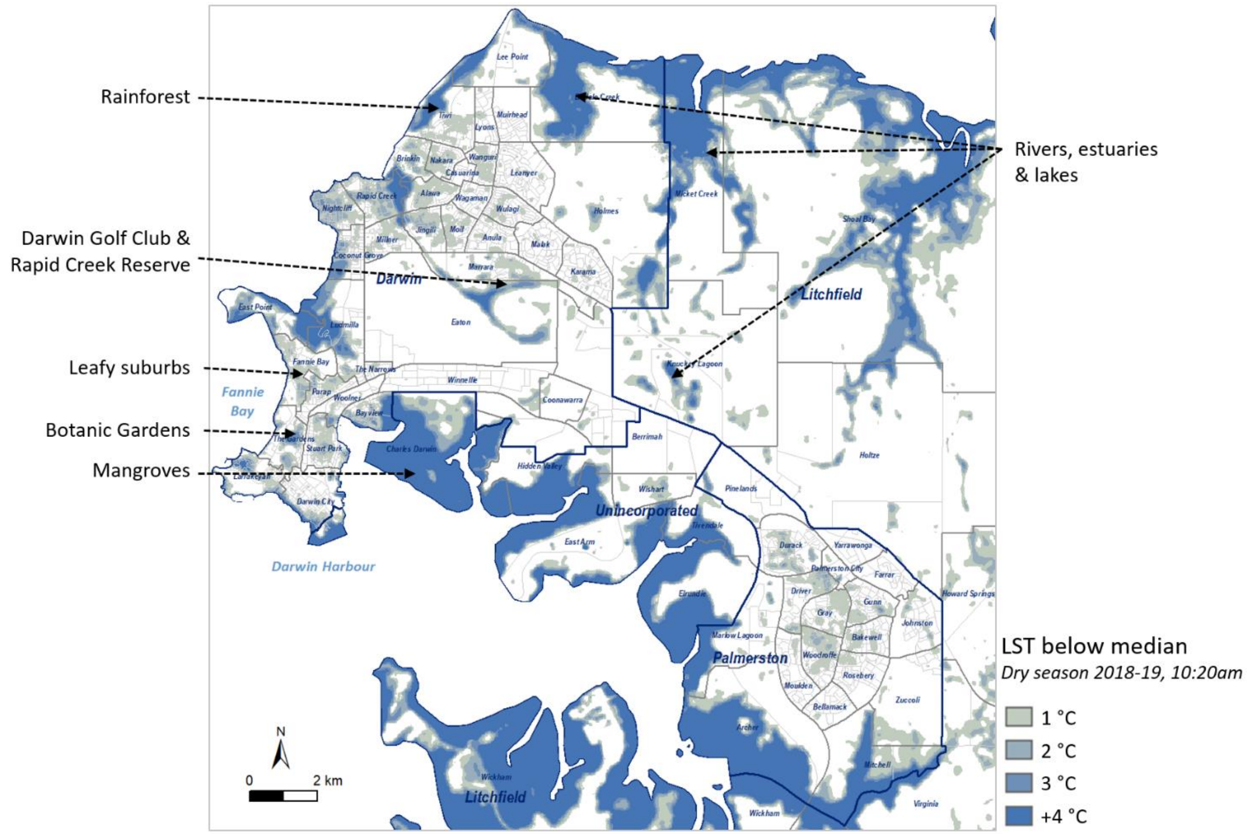


Figure 7. LST 'hot spots' and examples of areas or features with this characteristic.
Boundaries: LGA, suburb and Mesh Blocks (ABS, 2018).

4.5 Land surface temperature and land cover type

The mean surface temperature of different land cover classes was calculated and converted to departures from the coolest land class, 'Mangroves' (Figure 8). 'Monsoon rainforest' (+0.9 °C) and '*Lophostemon* communities' (+2.8 °C), commonly found in wet or swampy areas are the next coolest land cover classes. These results highlight the cooling influence that dense canopy cover and water have on surface temperatures. Apart from cooling benefits, these vegetation communities provide valuable ecosystem services. Mangroves, for example, provide flood, storm and erosion control; prevent salt water intrusion; provide breeding, spawning and nursery habitat for fish; sequester carbon; enhance biodiversity; and provide recreational opportunities (Brander et al., 2012).

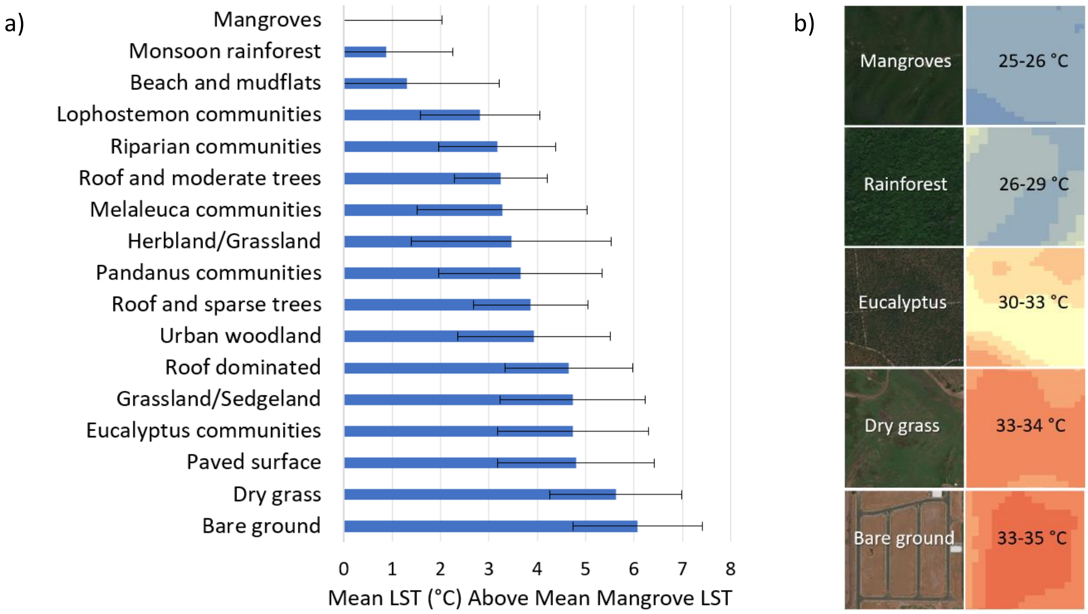


Figure 8. a) Mean LST and standard deviations for land cover classes showing departures from the coolest land cover class 'Mangroves'. b) Examples of LST for selected areas.

In contrast, 'Bare ground' is the hottest cover class (+6.1 °C) followed by 'Dry grass' (+5.6 °C), demonstrating that land that has been cleared or has a cover of sparse dry vegetation cover are some of the hottest land surfaces in Darwin. These 'natural' surfaces tend to cool down more quickly at night than paved surfaces and become relatively cooler during the wet season when the ground has a layer of green cover. 'Paved surface' (+4.8 °C) has the next highest mean land surface temperature but will not undergo seasonal changes in temperature in the same way as vegetated surfaces.

The next hottest classes are open structured vegetation communities '*Eucalyptus* communities' (+4.7 °C) and 'Grassland/Sedgeland' (+4.7 °C). Cured grass (Buyantuyev and Wu, 2010; Yuan and Bauer, 2007), an open canopy (Arnfield, 2003; Voogt and Oke, 2003) and more exposed ground will be contributing to the higher surface temperatures during the dry season. Grass and shrubs are distinctly cooler in the period between seasons when the foliage is green than later in the dry season (see examples in Table 3). 'Roof dominated' also has an average land surface temperature of +4.7 °C

While not specifically listed here, trees along streets, parks, and gardens also confer cooling benefits providing shade to people, vehicles and infrastructure. Trees provide other benefits to urban areas, for example, they improve air quality, provide habitat for wildlife, extend pavement maintenance times, and reduce erosion, energy use and noise (USEPA, n.d.).

4.6 Land surface temperatures and urban development

4.6.1 Land surface temperature and land-use planning zones

The mean land surface temperature and per cent tree canopy cover were calculated for Town Planning Zones. Temperature is expressed as departure from the coolest planning zone 'Conservation'. Figure 9 shows results for ten Town Planning Zones in Darwin's Greater Urban Area.

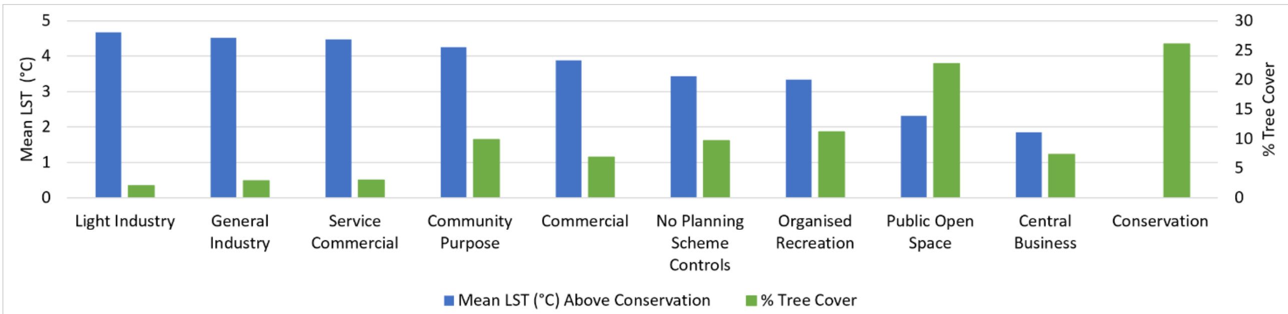


Figure 9. Mean LST (blue) and % tree cover (green) for ten Town Planning Zones.

'Light Industry' (+4.7 °C, 2% trees), 'General Industry' (+4.5 °C, 3% trees), and 'Service Commercial' (+4.5 °C, 3% trees) have the highest mean land surface temperature and the lowest mean tree cover. Industrial areas are the hottest land uses in many cities as they typically have few trees and are dominated by large roofs, buildings, roads and carparks (Guo et al., 2012; Mahmuda and Webb, 2016; Meyers et al., 2017; Weng et al., 2004). The east–west strip of high surface temperatures through Darwin and Palmerston coincides with the airport and the Industrial and Service Commercial areas of Winnellie, Pinelands and Yarrawonga adjacent to the Stuart Highway.

The cooling effect of trees and green spaces means that 'Conservation' (26% trees) and 'Public Open Space' (+2.3 °C, 23% trees) are, on average, the coolest planning zones. Other factors, such as shade cast from tall buildings can also create cool surfaces which may be the reason for the cooler 'Central Business' districts even though they have fewer trees.

Results for different residential zones are shown in Figure 10. On average, there is little difference between surface temperatures of different residential types, but the 'Single Dwelling Residential' class has a higher percentage of tree cover.

Single dwelling residences usually have more space to establish gardens and to grow trees than do higher density residential zones where gardens may be smaller or non-existent. 'High Density Residential' is only found in a small area close to the Darwin CBD and may be slightly cooler as a result of other factors such as proximity to the coast or morning shade cast from tall buildings, but this result is speculative.

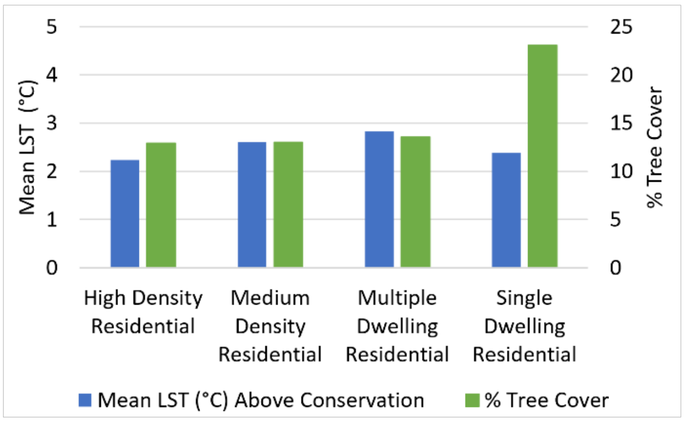
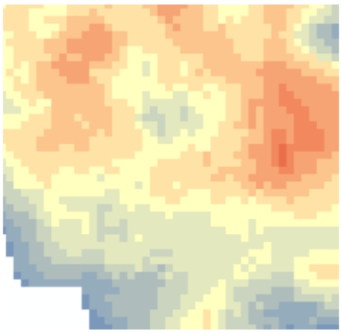
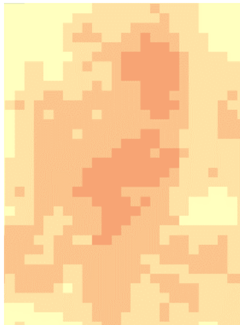


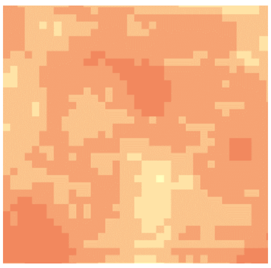
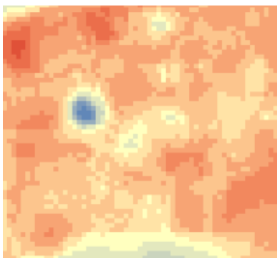
Figure 10. Mean LST (blue) and % tree cover (green) for Residential Town Planning Zones.

4.6.2 Land surface temperatures in different land-use types

Different land cover types and Town Planning Zones have different mean surface temperature profiles, but within each of these broad classes there are a range of surface temperatures. Understanding the types of features that are commonly associated with high and low surface temperatures can assist planners with choosing materials or land cover types to reduce urban heat. Examples of surface temperatures within Town Planning Zones are shown in Table 2.

Table 2. Selected urban areas showing the aerial image (ESRI) and thermal image.

<table>
<tr><td colspan="3">Commercial areas often have extensive roofing, car parks, roads and few trees. While shade cast from buildings and built structures create shade, radiant heat stored in the building materials and urban canyons during the day add to the night-time urban heat island effect. Incorporating breezeways, cool building materials and shade structures can help to reduce urban temperatures in public places.</td></tr>
<tr><td>Darwin City is surrounded on three sides by water and is ideally placed to take advantage of onshore breezes channelled into the city. There is an 8 °C range in surface temperatures across the area shown, from 33–35 °C for bare ground/asphalt, to 27–28 °C in Civic and Bicentennial parks. The shady trees and irrigated grass in these parks provide cool retreats in the city. The tall buildings in the centre of the image are casting shade over nearby surfaces.
 </td><td>Large suburban shopping centres have extensive roofing, car parks and few trees. The outdoor carparks at Casuarina Shopping Centre (33 °C) have few trees and little shade for vehicles and pedestrians.
 </td><td>
</td></tr>
</table>

<table>
<tr><td colspan="3">Industrial areas typically have extensive roofing, car parks, roads, few trees, and higher surface temperatures.</td></tr>
<tr><td>Winnellie has large areas of roofing, paving and few trees, and LST in the image below has reached 34 °C. Cool roofing materials and more green cover could reduce surface temperatures in industrial areas, but care is required to avoid glare when increasing the reflectivity of surfaces.
 </td><td>Wharf areas and transport/storage/handling hubs have little shade and large areas of paved surfaces for loading, stockpiling and storing bulk materials and cargo. Temperatures at East Arm have reached 35 °C. The blue roofs are likely to be remote sensing anomalies (errors) caused by highly reflective roofs and is an example of when results need to be treated with caution.
 </td><td>
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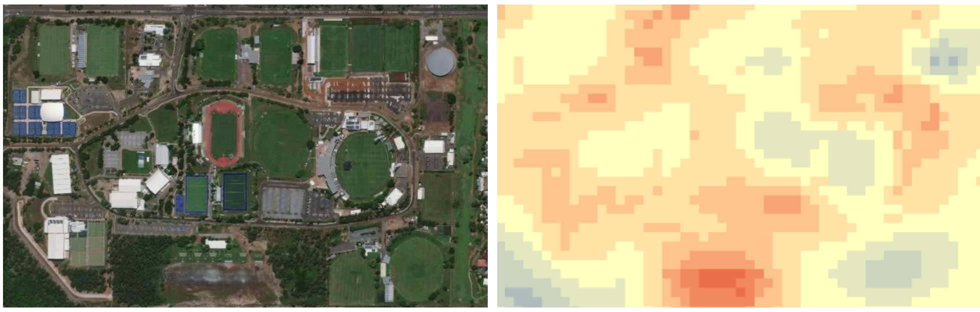
Playing fields

The surface temperatures of playing fields vary with surface type and soil moisture. This is evident at the Marrara Sporting Complex, where there is a 7 °C range in surface temperatures between playing surfaces; e.g. shooting range (34–35 °C), roofs and carparks (32–33 °C), artificial playing surfaces (31–32 °C), golf club fairways (29–30 °C), and irrigated sports fields (28–29 °C). The irrigated fields demonstrate the cooling benefits provided by green vegetation and soil moisture through evapotranspiration.



Residential areas can vary in the amount of tree cover, irrigated gardens and dwelling density, factors that can influence land surface temperatures.

New residential areas often have higher density housing, more bare ground and little tree cover; however, they will become cooler over time as gardens and trees become established. Land surface temperatures in Muirhead (below) range between 33–34 °C for bare ground and 30–32 °C in built-up areas.

Leafy residential areas typically have established gardens, more tree cover, shaded footpaths, and verges wide enough to accommodate large shade trees. The residences in Stuart Park (29–30 °C) are near irrigated parks.

4.6.3 Land surface temperatures at the hospital and airport

Three areas were identified as important areas for investigation of potential heat mitigation activities, the Darwin CBD, The Royal Darwin Hospital, and the Darwin International Airport.

The Darwin CBD is the focus of the Darwin City Deal (Australian Government et al., 2018). Temperature data has already been collected at a fine scale in the Darwin CBD by the University of New South Wales (Santamouris et al., 2017). Ongoing monitoring with in-situ thermal sensors by the Darwin City Council and UNSW have this area well covered for data collection and apart from presenting a map of land surface temperature for the CBD (Figure 16), will not be covered in further detail in this report.

A workshop held between researchers from CSIRO, CDU, and UNSW identified the Royal Darwin Hospital as a potential site for trialling heat mitigation strategies to create a cooler environment (Lin et al., 2020). The hospital was chosen as it is a place where vulnerable people present with heat-related health issues and illnesses that are exacerbated by high temperatures (Bauert, 2005). The hospital is also a place where heat sensitive groups are present (e.g. elderly, young children, and pregnant women).

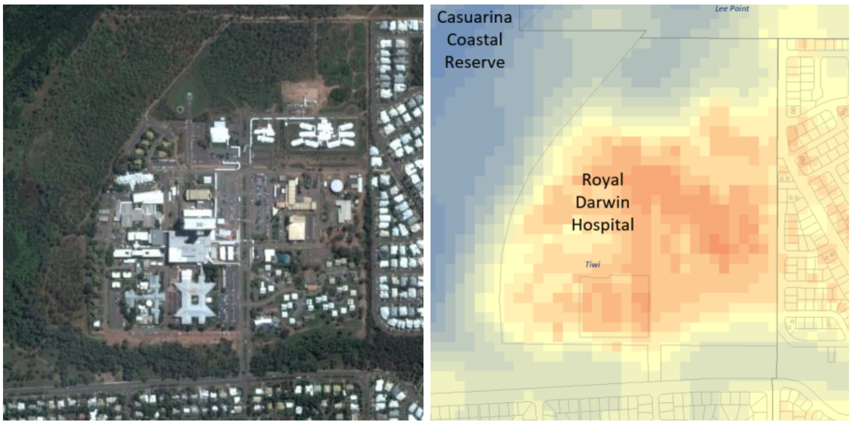
The Darwin International Airport – a combined military and civilian airport – is located on a large area of land in the middle of Darwin. The airport has been a focus of discussion over the years because of its location in the heart of the city and whether it should be moved to an alternative location further away from the city

(Brown, 2019; Weller and Bolleter, 2013). The airport is also part of a strip of high land surface temperatures through the centre of Darwin.

Two maps of land surface temperatures at Royal Darwin Hospital and Darwin International Airport and surrounding suburbs are shown in Table 3; one in the transition period (Apr–May) and one in the dry season (Jun–Aug). These maps highlight the differences that seasonal vegetation cover can make to surface temperature with relatively higher temperatures in the dry season when the groundcover is dryer and soil moisture is lower. They also show that older suburbs with a more established cover of trees and gardens have cooler surface temperatures than newer suburbs that have little tree cover and more paving and bare ground.

Table 3. Seasonal differences in LST at Royal Darwin Hospital and Darwin International Airport.
Imagery courtesy of Google Earth.

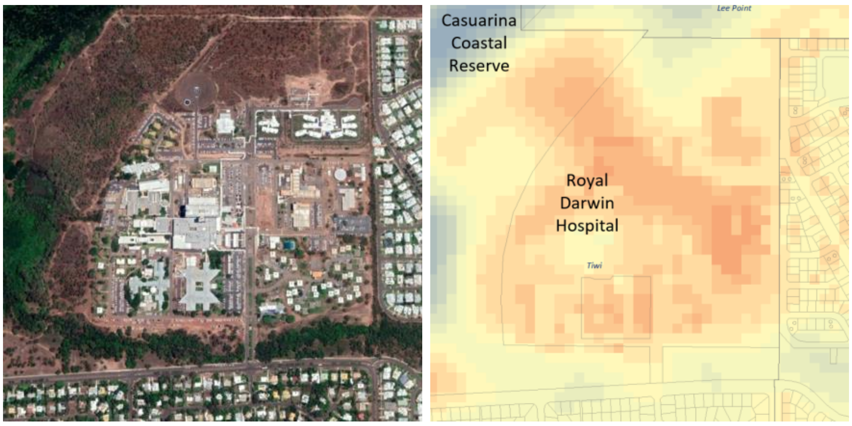
Royal Darwin Hospital is located near the coast in the northern suburbs of Darwin. The site is dominated by buildings and outdoor car parks that have relatively high surface temperatures. The site is bordered by vegetation on three sides. The leafy coastal forest in the Casuarina Coastal Reserve is 'cool' in both seasons. The open canopy forest to the north and west of the hospital is distinctly cooler in the transition period (top image) when the groundcover is greener than when the grasses have dried (bottom image). The suburb of Tiwi south of the hospital has more trees and established gardens and cooler surface temperatures than the newer suburb of Lyons to the east of the hospital. Shady parks, irrigated gardens and wide treed verges help to reduce surface temperatures in suburban areas.



Seasonal transition period

Left: 1 May 2017

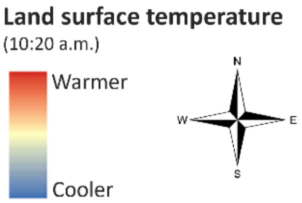
Right: LST (Apr-May)



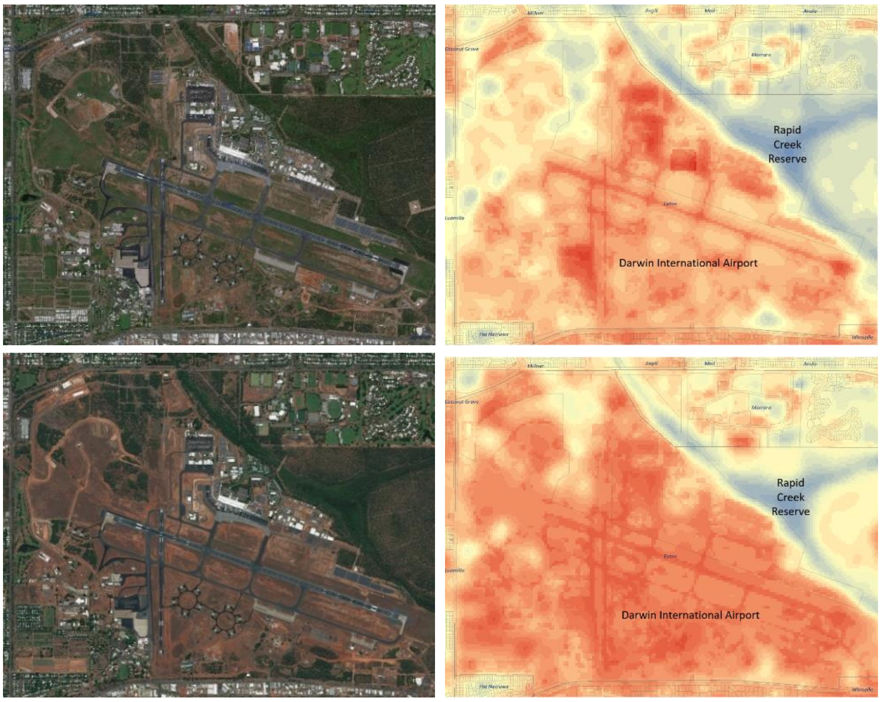
Dry season

Left: 19 October 2017

Right: LST (Jun-Aug)



Darwin International Airport has large areas of paving, grass and bare ground. As the green grass in the wet season dries over the winter months, surface temperatures become relatively warmer. Areas with sparse dry grass can be hot during the day but tend to cool off more quickly at night. In contrast, the Rapid Creek Reserve has riverine vegetation that provides cooling benefits through tree shade and evapotranspiration even in dry months.



Seasonal transition period

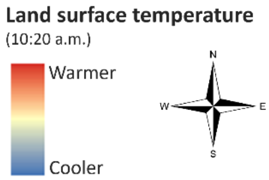
Left: 1 May 2017

Right: LST (Apr-May)

Dry season

Left: 19 October 2017

Right: LST (Jun-Aug)



4.7 Neighbourhood land surface temperatures and urban features

We used multiple linear regression modelling to determine the contribution that different urban features such as dwelling density, distance from the coast, bare ground, roads and paths, buildings, and tree cover make to land surface temperatures in residential neighbourhoods. Neighbourhoods were defined as being ABS 2016 Mesh Block boundaries classed as 'Residential' (ABS, 2016a) within the Greater Urban Area (n=1097). Median land surface temperature was calculated for each Mesh Block and converted to degrees Celsius above the coolest Mesh Block.

The data show that there is a 7.5 °C mean LST difference between the warmest and coolest residential neighbourhoods. The final model ($R^2 = 0.592$, $p < 0.001$) showed that residential Mesh Blocks are cooler when they have more tree cover, less bare ground, roads and paths, and are closer to the coast (Table 4). Figure 11 shows the three predictors plotted against the median land surface temperatures of Mesh Blocks.

Table 4. Summary statistics from the multiple linear regression analysis.

Variable	*Coefficients*	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	3.059	0.069	44.25	7.2E-246	2.923	3.194
Tree cover (%)	-0.023	0.002	-12.93	1.1E-35	-0.027	-0.020
Bare ground, roads & paths (%)	0.038	0.002	22.32	3.2E-91	0.035	0.042
Distance from the Coast (km)	0.140	0.009	15.70	2.9E-50	0.123	0.157

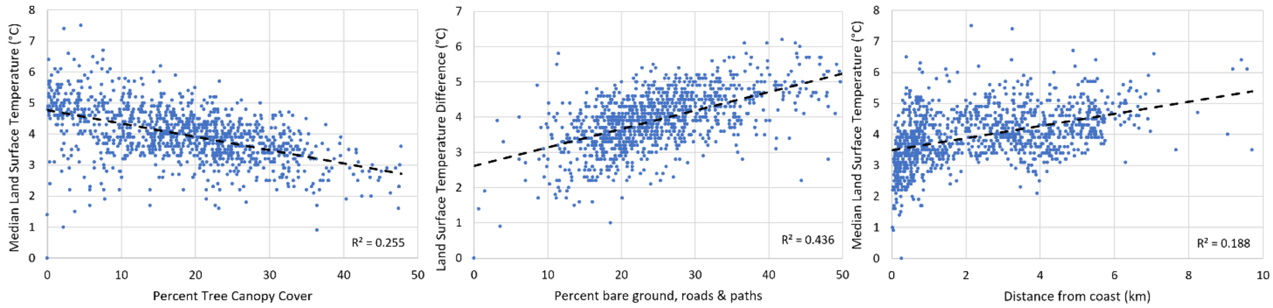


Figure 11. Departures from baseline median Mesh Block LST plotted against observed values for three modelled landscape characteristics.

Not all cool Mesh Blocks have a high percentage of tree cover (Figure 11) suggesting that other factors, such as the presence of water, the use of light coloured and cool building materials, the radiative geometry of the built environment, and local wind conditions can also contribute to cooler temperatures in Darwin as described in Santamouris et al. (2019). Aerial views of four residential Mesh Blocks show that neighbourhoods with different amounts of tree cover can have similar mean surface temperatures. For example, Mesh Blocks in Driver and Cullen Bay have similar median LST, but Driver has a considerable tree cover while Cullen Bay is mostly water (Figure 11).

An example of four Mesh Blocks shown in Figure 11 with different features can be characterised as:

A - High rise urban (Darwin City): Hotter (32.9 °C), few trees (1.8%), extensive bare ground and paving (60%)
B - New suburban (Muirhead): Hotter (32.4 °C), few trees (<1%), extensive bare ground and paving (40%)
C - Older suburban (Driver): Cooler (28.9 °C), many trees (46%), little bare ground and paving (10%)
D - Maritime (Cullen Bay): Cooler (28.3 °C), few trees (4%), little bare ground and paving (14%), water

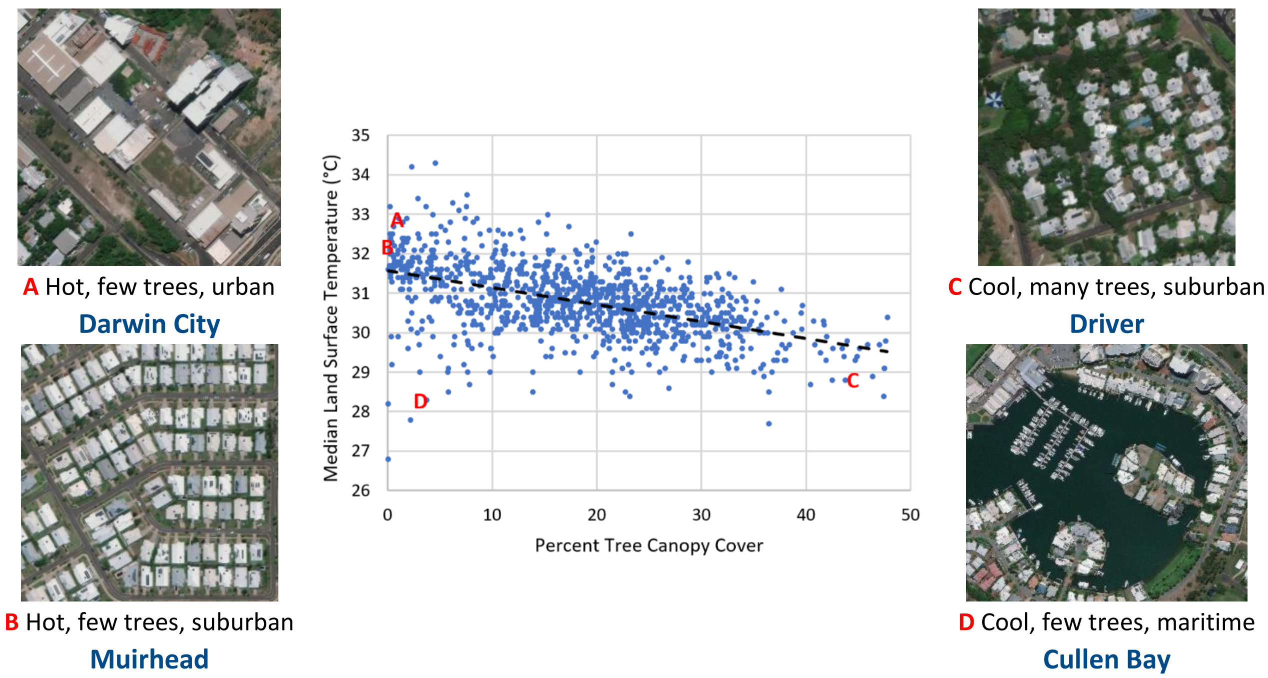


Figure 12. Median dry season LST (Jun-Aug, 2018-19 at 10:20 a.m.) and features of selected residential Mesh Block 'neighbourhoods' (A-E).
Imagery: Esri World Imagery.

4.8 Potential planting sites to reduce land surface temperatures

Trees and other green vegetation provide cooling benefits through evapotranspiration and shade (Bowler et al., 2010), but the benefits vary with tree size, species, and the amount of leaf area. Selecting where to plant vegetation to achieve cooling benefits requires knowledge of 'where it is hot' and 'where green vegetation/trees could potentially be planted'. A preliminary assessment of 'potential' planting locations is presented for an area within the City of Darwin, with land surface temperatures being used to address 'where it is hot', and 'bare ground or grass' being used to address 'where green vegetation/trees could potentially be planted'. Areas where higher land surface temperatures coincide with areas of bare ground or grass are found in areas on the outskirts of Darwin, several sporting areas, industrial areas, the airport and several smaller areas throughout the suburbs (Figure 13). These areas are only 'potential' sites; however, as it is clear that shrubs and trees cannot be planted in areas where bare ground or grass serves an important function, such as at the airport where they would interfere with take-off and landing.

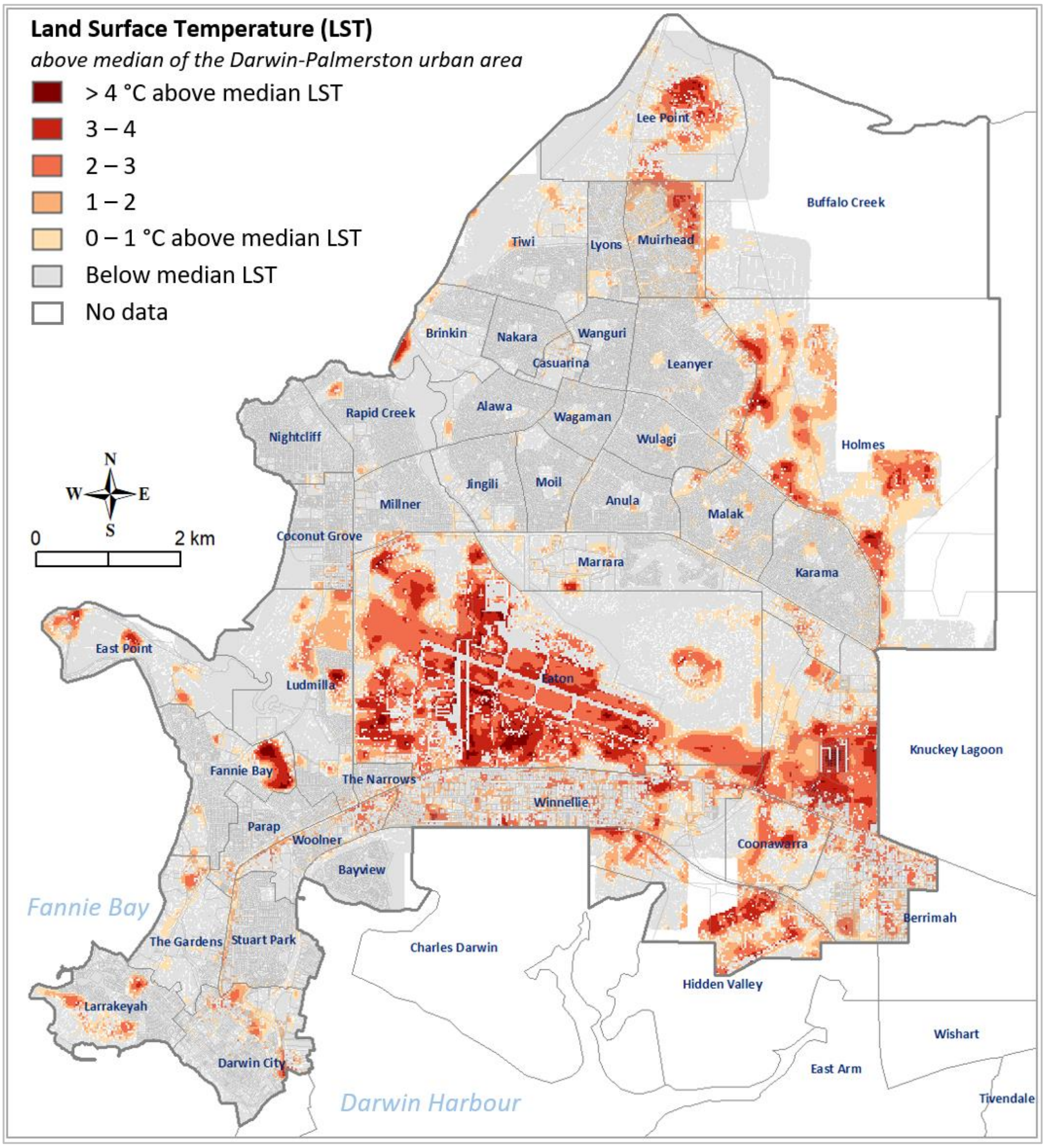


Figure 13. Areas where areas of high LST coincide with areas of grass or bare ground.

Boundaries: LGA, suburb (ABS, 2018) and land parcels (NTG, 2019). Source: Ground cover (Pitney Bowes, 2019).

5 Neighbourhood heat-health vulnerability

To reduce urban heat and heat-health risk for vulnerable population requires the identification of physical and socioeconomic characteristics at a spatial scale that is relevant to planning (Yoo, 2018). In this study we have defined a 'neighbourhood' as ABS Mesh Blocks, an area that contains between 30 and 60 dwellings (ABS, 2016a). Aggregation of data maintains confidentiality of individuals and households. Mesh Blocks tend to be larger in size in peri-urban areas but are more consistent in size in suburban and urban areas. Within the Greater Urban Area there are 1172 Mesh Blocks.

The Neighbourhood Heat-Health Vulnerability Index (NHVI) was created to assist with identifying areas where more residents have a higher risk of heat-related illness, fewer economic resources to cool their homes or invest in adaptation strategies and are exposed to higher urban temperatures.

The NHVI is constructed using median land surface temperature of each Mesh Block to estimate potential exposure to higher temperatures. Heat-health risk is estimated using data from the ABS 2016 Census on the number of people in each Mesh Block who are elderly (65 years and older), or very young (under 5 years old), or identify as Aboriginal and Torres Strait Islander, or are living in public housing or low-income households.

For each Mesh Block, median land surface temperature was combined with the neighbourhood heat-health risk score to derive the NHVI. The Mesh Blocks were ranked from the highest to the lowest vulnerability, from the Mesh Blocks with the highest (100) to the lowest (0) vulnerability score. See Section 3.3 for a rationale behind the index and a full description of how the NHVI was constructed.

This report includes maps of: (1) median land surface temperatures of Mesh Blocks, (2) neighbourhood heat-health risk, and (3) NHVI scores. Maps are provided below for the whole of the Greater Urban Area (Figure 14) and in Appendices for the City of Darwin (Figure 17) and the City of Palmerston (Figure 19).

The 15 Mesh Blocks with the highest NHVI (ranks above 99) in the Greater urban are located in:

- City of Darwin: Ludmilla, Tiwi, Berrima, The Narrow, Fannie Bay, Marrara, Coconut Grove, and Darwin City
- City of Palmerston: Johnston, Gray, Bellamack, and Moulden
- Litchfield: Holtze

These Mesh Blocks have higher median land surface temperatures and potentially more people who are either living in low-income households, public housing, Indigenous communities, aged care facilities, or correctional facilities, based on ABS 2016 Census data. Suburbs that have the highest number of Mesh Blocks in the top 5% of NHVI scores are listed below with the number of Mesh Blocks in each of the suburbs in brackets.

- The City of Darwin: Karama (5), Malak (5), Coconut Grove (4), and Berrimah (3)
- The City of Palmerston: Moulden (15), Gray (10), and Driver (4)
- Litchfield: Coolalinga (3)

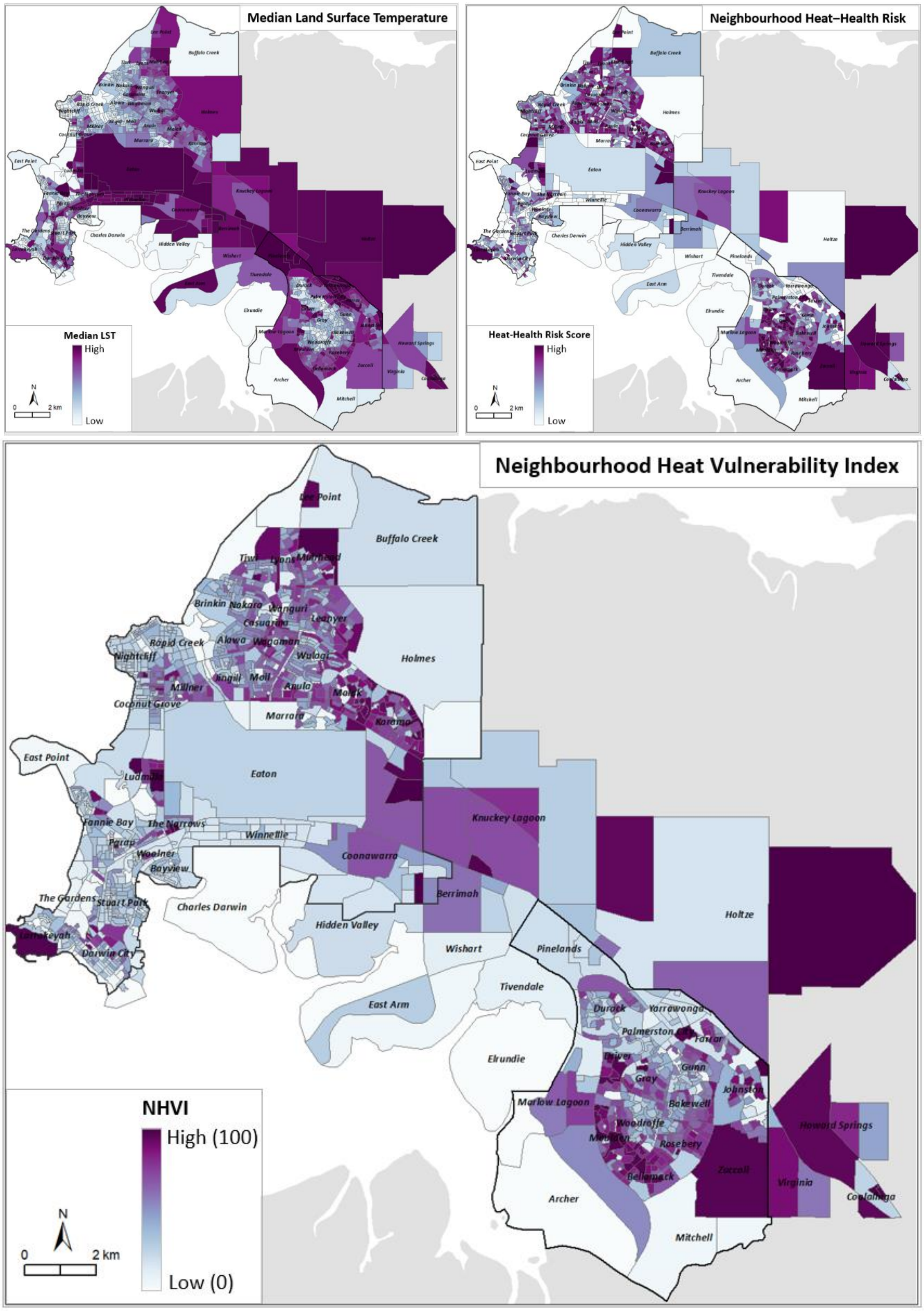


Figure 14. Greater Urban Area: (bottom) Neighbourhood Heat-Health Vulnerability Index (NHVI) for Mesh Blocks derived from (top left) median LST (dry season 2018-19, 10:20 a.m.) and (top right) Neighbourhood Heat-Health Risk based on ABS 2016 Census data.

Boundaries: LGA, suburb and Mesh Blocks (ABS, 2018).

6 Conclusion and potential next steps

This report and the spatial data developed in this project provide resources to support the Northern Territory Government, the City of Darwin and the City of Palmerston to take actions to mitigate urban heat in Darwin. It shows that land surface temperatures vary with different types of built or natural surface cover, the type and seasonality of vegetation, the presence of water, and distance from the coast.

Hotter daytime temperatures are found in areas with high concentrations of buildings and paved surfaces common in commercial and industrial areas, large carparks and major roads. These materials have high heat capacity and cool down slowly at night, contributing to the urban heat island effect. Hotter areas are also found where there is extensive bare ground and sparse dry vegetation, and in the dry season in areas such as at the airport, construction sites and rural pasture. While these natural surfaces are hotter during the day, they tend to cool down quickly at night. Cooler surface temperatures during the day are found where there is water, shade, and green vegetation, particularly if the vegetation has a dense canopy and remains green throughout the year.

The focus of this project was the Greater Urban Area, and complements previous work done in the Darwin CBD by the University of NSW (Santamouris et al., 2019; Santamouris et al., 2017). Combined, these studies can help identify priority areas for heat mitigation actions for the improvement of thermal comfort for Darwin’s residents. The aim of heat mitigation is to reduce the absorption of solar radiation into urban structures, increase emissivity of surfaces so that less heat is stored in the materials, increase shade and evaporative processes in ways that do not increase humidity, and embrace urban design so that heat dissipates quickly into the cooler atmosphere at night. Mitigating urban heat in Darwin without increasing humidity presents a particular challenge for planners. Key mitigation strategies for reducing heat without increasing humidity can be found in the companion report (Lin et al., 2020).

The Neighbourhood Heat-Health Vulnerability Index presented in this report was designed to assist with identifying areas for targeted heat mitigation actions in places that will benefit vulnerable groups. The social-economic data that underpins the mapping was developed using data from the ABS 2016 Census of Population and Housing. This mapping could be built upon in the future to capture changes since 2016, and by adding local knowledge of high outdoor activity areas. These changes could be assisted through liaison with service providers and community groups to find appropriate ways to reduce heat exposure for Darwin’s most vulnerable residents.

Some suggestions for extending this research include:

- Extend the results in this report and other thermal research in Darwin (e.g. Santamouris et al. (2017), 202020 Vision (2017), (Good, 2016)) to investigate the relationships between land surface temperature, air temperature, humidity, wind, and time of day and how it affects thermal comfort.
- Monitor urban heat over time using a range of on-ground and remote sensors to evaluate heat mitigation actions and identify new hotspots.
- Combine the results from different monitoring, experimentation and modelling activities to develop models for the broader distribution of heat across Darwin at different times of the day and in different seasons. Use these models to develop scenarios for the heat mitigation options outlined by Lin et al. (2020).
- Combine the results in this report with local knowledge and previous health research (e.g. Goldie et al. (2015), Oppermann et al. (2017), Zander et al. (2015)) to further identify priority areas for targeted heat mitigation actions that will benefit the most exposed and vulnerable people in Darwin.

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A.1 City of Darwin

A.1.1 Land surface temperatures (City of Darwin)

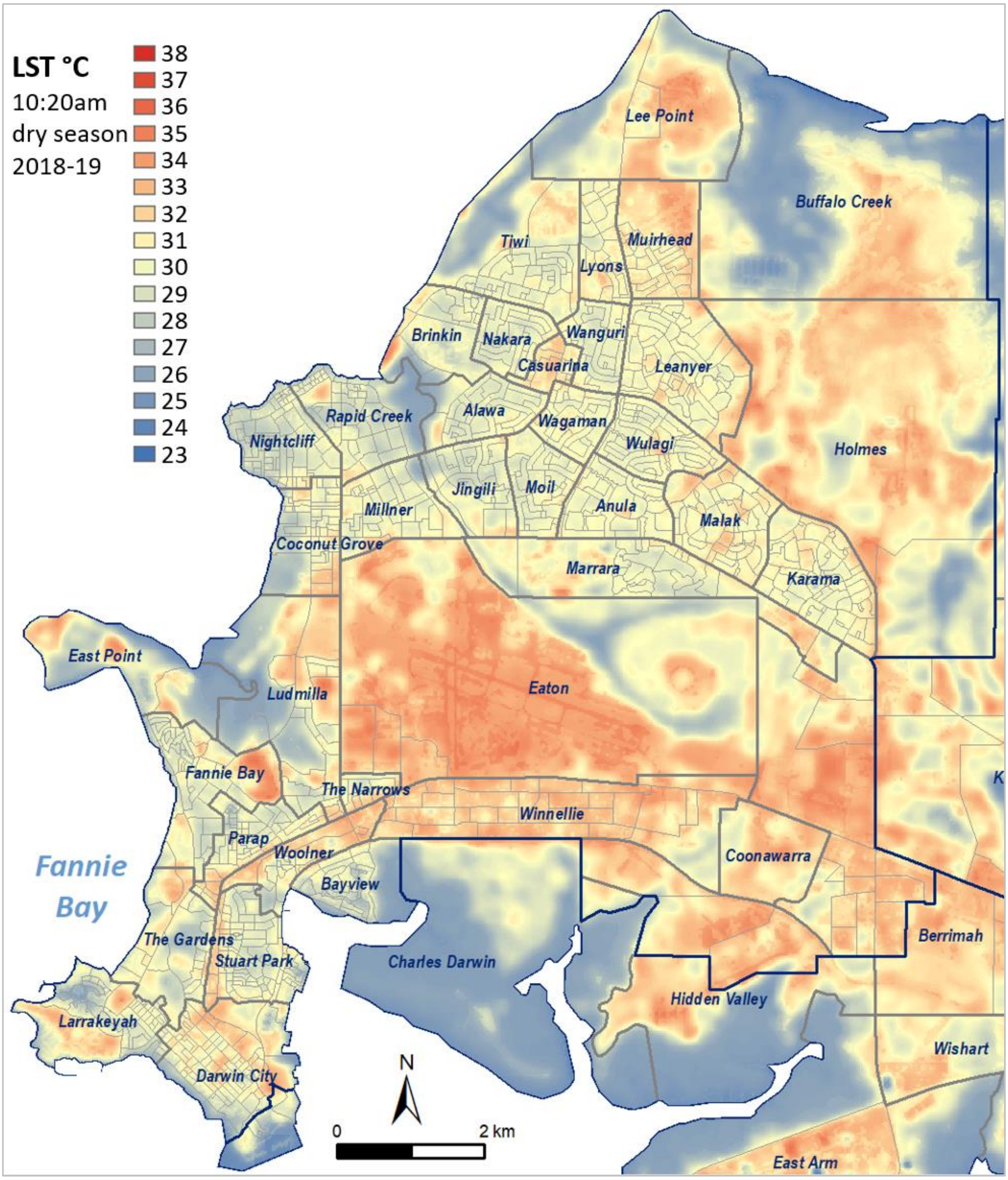

Figure 15. Dry season LST for the City of Darwin based on Landsat 8 thermal imagery for Jun–Aug in 2018–19 at 10:20 a.m.

Boundaries: LGA, suburb and Mesh Block boundaries (ABS, 2018).

A.1.2 Land surface temperatures (Central Darwin)

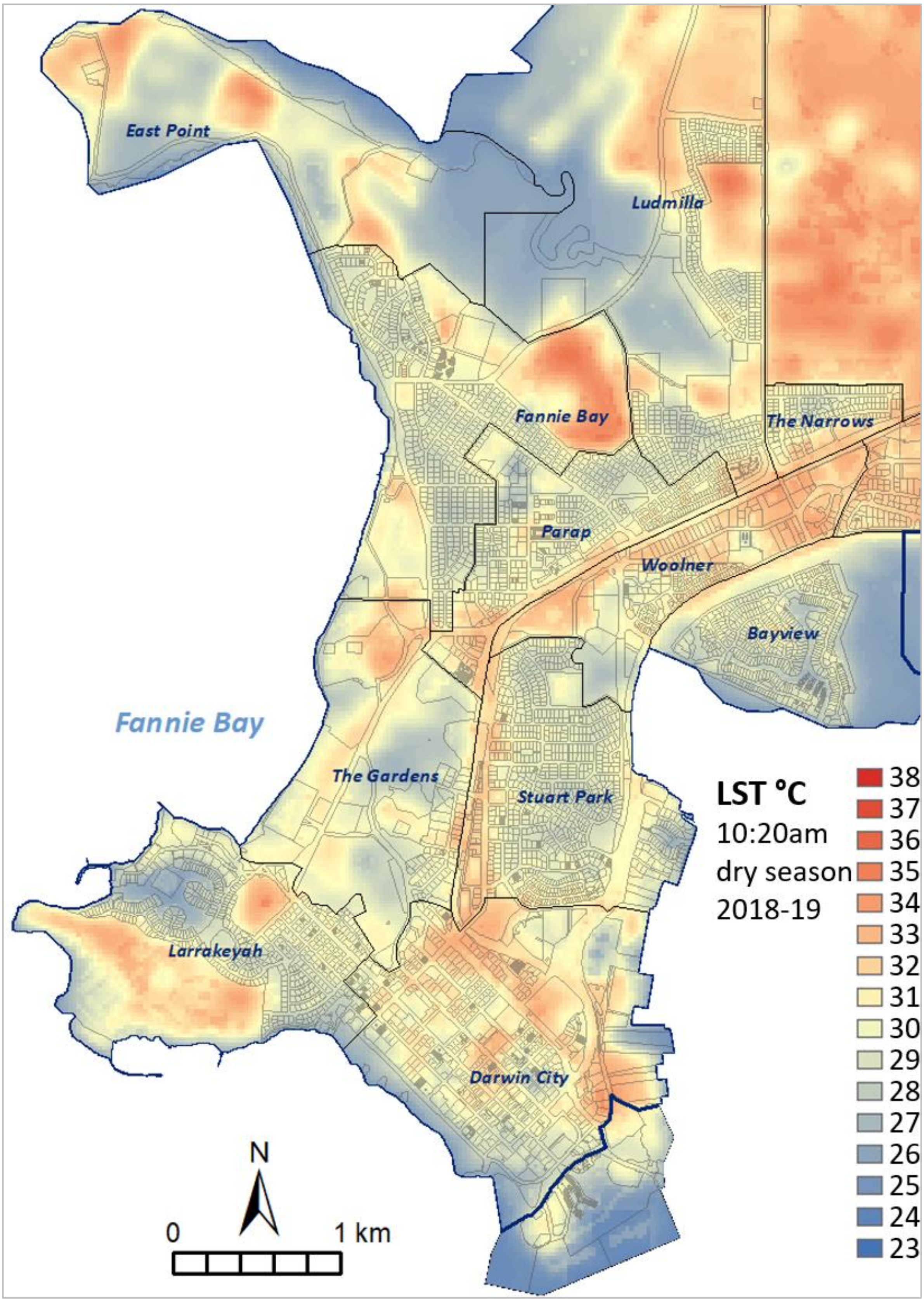

Figure 16. Dry season LST for Central Darwin based on Landsat 8 thermal imagery for Jun–Aug in 2018–19 at 10:20 a.m.

Boundaries: LGA, suburb (ABS, 2018) and land parcels (NTG, 2019).

A.1.3 Neighbourhood Heat-Health Vulnerability Index

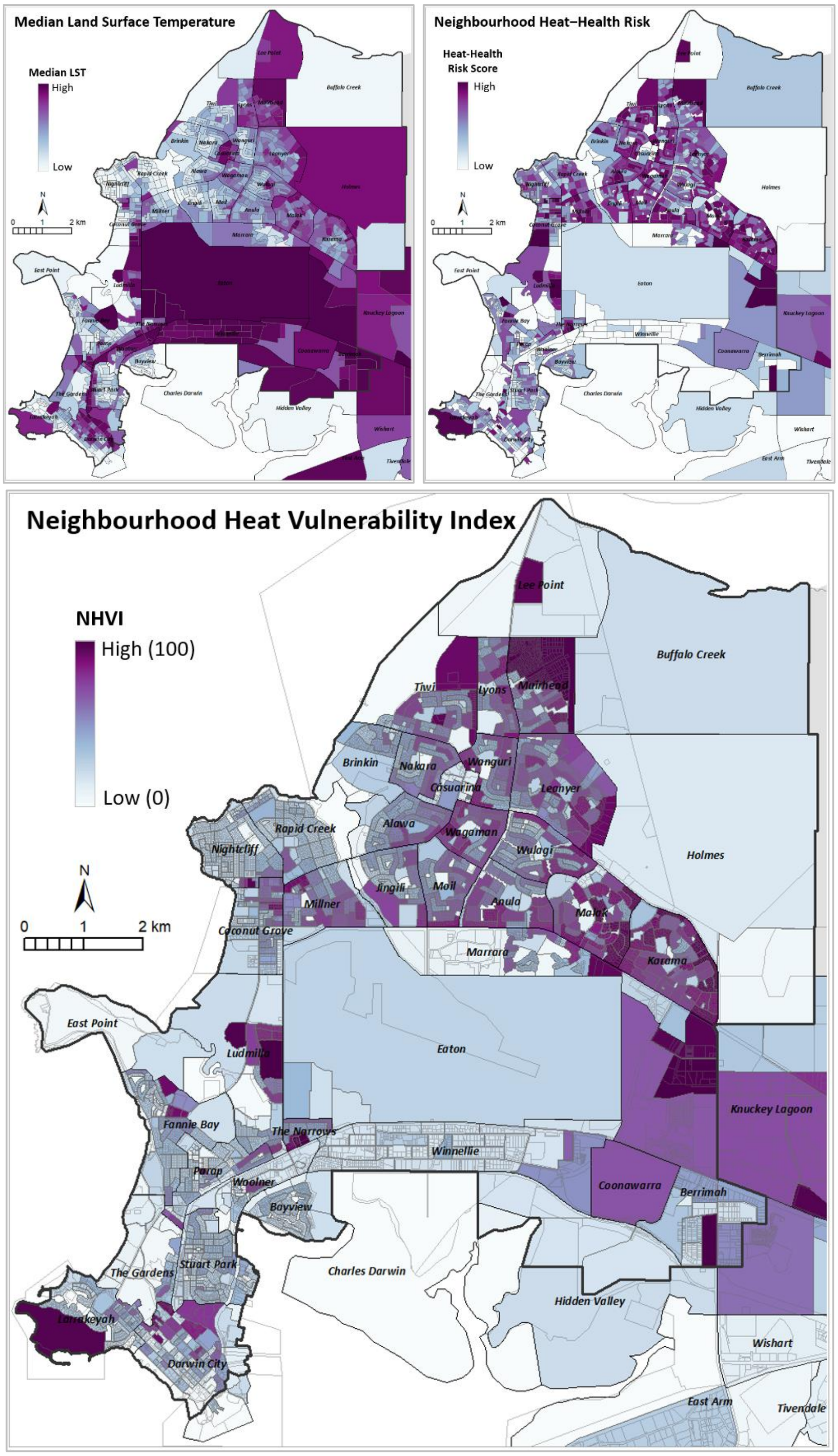

Figure 17. City of Darwin: (bottom) Neighbourhood Heat-Health Vulnerability Index (NHVI) for Mesh Blocks derived from (top left) median LST (dry season 2018-19, 10:20 a.m.) and (top right) Neighbourhood Heat-Health Risk based on ABS 2016 Census data.

Boundaries: LGA, suburb (ABS, 2018) and land parcels (NTG, 2019).

A.2 City of Palmerston

A.2.1 Land surface temperatures

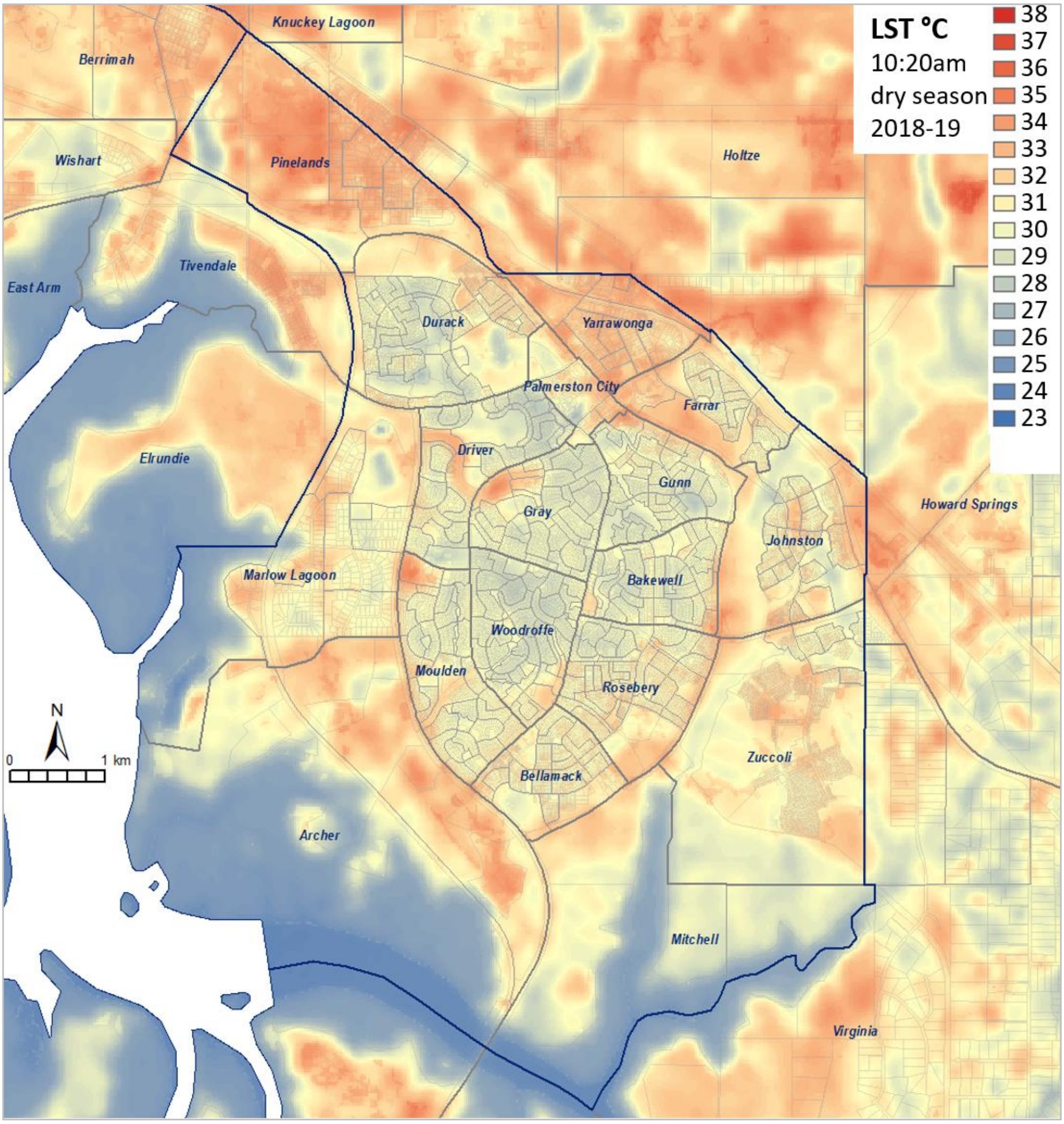

Figure 18. Dry season LST for the City of Palmerston based on Landsat 8 thermal imagery for Jun–Aug in 2018–19 at 10:20 a.m.

Boundaries: LGA, suburb (ABS, 2018) and land parcels (NTG, 2019).

A.2.2 Neighbourhood Heat-Health Vulnerability Index

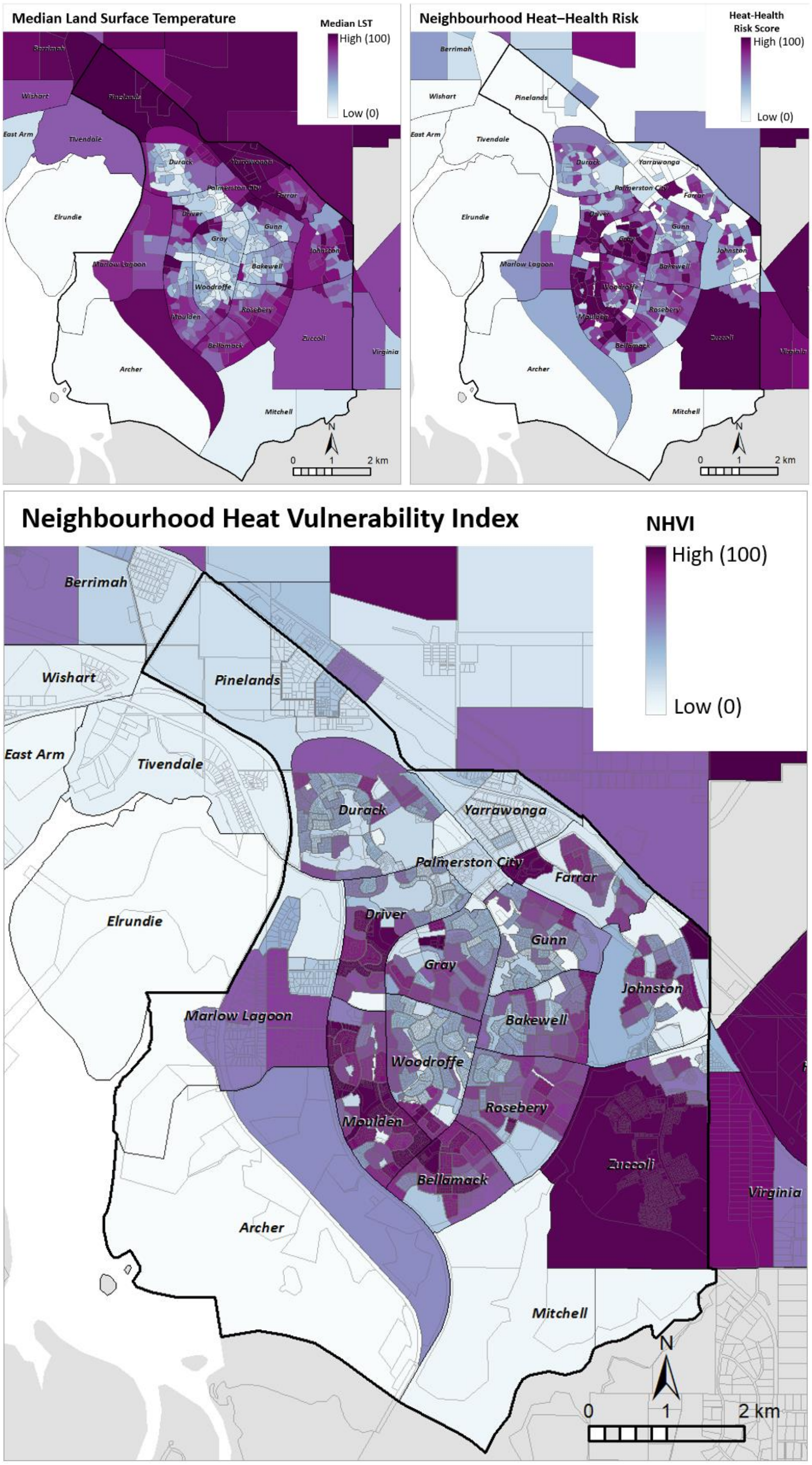

Figure 19. City of Palmerston: (bottom) Neighbourhood Heat-Health Vulnerability Index (NHVI) for Mesh Blocks derived from (top left) median LST (dry season 2018-19, 10:20 a.m.) and (top right) Neighbourhood Heat-Health Risk based on ABS 2016 Census data.

Boundaries: LGA, suburb (ABS, 2018) and land parcels (NTG, 2019).

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Contact us

1300 363 400
+61 3 9545 2176
csiroenquiries@csiro.au
www.csiro.au

For further information

Jacqui Meyers
CSIRO Land & Water
+61 2 6246 4384
Jacqui.Meyers@csiro.au

Brenda B. Lin
CSIRO Land & Water
+61 7 3833 5647
Brenda Lin@csiro.au

https://research.csiro.au/darwinlivinglab/