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RESEARCH ARTICLE

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A strontium isoscape of north-east Australia for human provenance and repatriation

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Abstract

It has been estimated that up to 25% of Indigenous human remains held in Australian institutions are unprovenanced. Geochemical tracers like strontium isotope ratios ($^{87}Sr/^{86}Sr$) have been used globally for over 40 years to discern human provenance and provide independent data to aid in repatriation efforts. To reliably apply this technology, landscape $^{87}Sr/^{86}Sr$ isotope ratio variability must be quantified. In Australia, only a few studies have used this technique and they are lacking in detail. Here, we present Australia's first regional strontium isotope ratio variability study. We measured strontium isotope ratios in soil, plant, water, and faunal material throughout Cape York, Queensland, the most northerly point of mainland Australia. Results show a close correlation between surface soil leachates, vegetation, surface water, and faunal $^{87}Sr/^{86}Sr$ results with extremely high values (0.78664) associated with ancient Precambrian geology. Our study suggests that measuring $^{87}Sr/^{86}Sr$ in soil and plant samples offer a reliable approach for assessing regional Sr isotope distribution, although the inclusion of mammal and freshwater samples is also important to assess exogenous inputs. This study provides an important tool for modern and prehistoric provenance studies and may aid in answering some of Australia's most enduring archaeological questions.

KEYWORDS

bioarchaeology, biogeochemistry, Cape York, isotope geochemistry, strontium isotopes

1 | INTRODUCTION

This study was part of an Australian Research Council funded research project that sought to improve our ability to provenance human skeletal remains from Queensland (QLD), Australia that currently cannot be repatriated due to a lack of geographical information. Strontium isotope ratios ($^{87}Sr/^{86}Sr$) are commonly used in archaeology and forensic anthropology as geochemical tracers for assessing provenance and migration (Makarewicz & Sealy, 2015). However, before Sr isotope ratios can be used to assign skeletal remains to a specific geographic region, the spatial variability of the $^{87}Sr/^{86}Sr$ isotope ratios in the landscape must be established. Between 2015 and 2018, we undertook sampling campaigns to establish the $^{87}Sr/^{86}Sr$ ratio distribution throughout Cape York, a peninsula of roughly 288,000 km^2 in the far north-east Australia (Figure 1). The project also investigated a series of prehistoric and contact period burials throughout Cape York (Adams, Martin, Phillips, Macgregor, & Westaway, 2018; Adams, Williams, Flinders, & Westaway, 2018), providing case studies to test this technique.

Commonly, Sr isotope ratio distribution studies rely on a suite of different sample types, with little focus on how reliably geological Sr output is transferred through vegetation, hydrology,

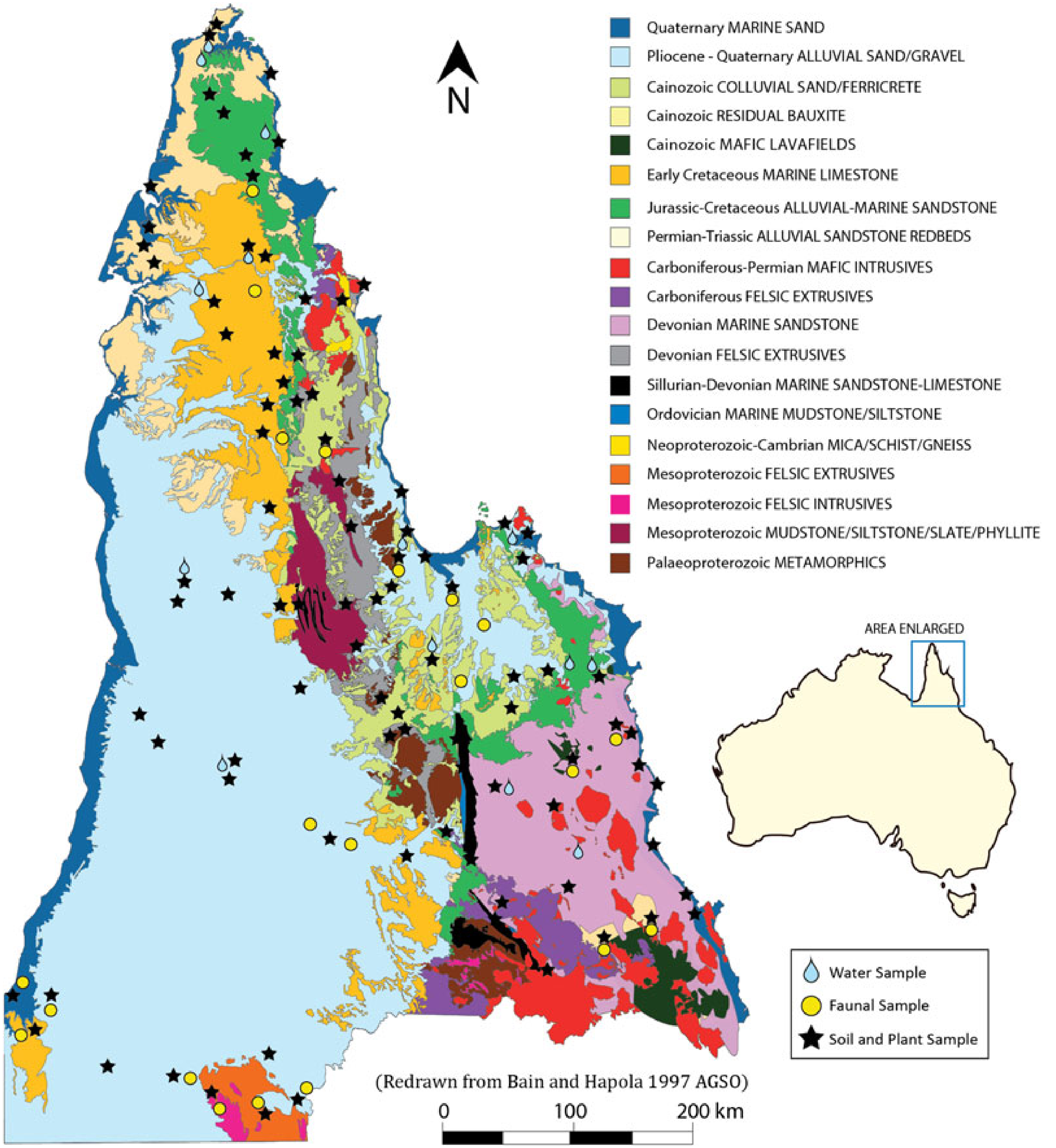

FIGURE 1 Cape York bedrock geology (Bain & Haipola, 1997b) with sample sites [Color figure can be viewed at wileyonlinelibrary.com]

and mammalian body tissue (Vaiglova et al., 2018; Wang, Tang, & Dong, 2018; Whelton et al., 2018). These factors are case-specific and altered by environmental proxies like topography, weathering rates, climate, and anthropogenic disturbance (Bentley, 2006). Here we present Australia's first Sr isoscape and investigate how reliably bioavailable $^{87}Sr/^{86}Sr$ is transferred through vegetation, hydrology, and mammalian body tissue in north-east Australia to gauge confounding factors and assess the technique for human mobility studies.

1.1 | Cape York

Cape York forms the north-eastern corner of Australia, bounded on the west by the Gulf of Carpentaria and on the east by the Coral Sea. Its southern boundary conventionally follows the 16°S latitudinal gridline. The climate of Cape York is strongly influenced by the Australian monsoon and therefore the Cape experiences a wet season and a dry season. The wet season occurs in the summer months, from November to April (Woinarski, Mackey, Nix, & Traill, 2007). Tropical cyclones are common in this season (Luly, Grindrod, & Penny, 2006). The Great Dividing Range, running parallel to the coast of Cape York, creates orographic rains in the eastern and upland districts through the dry winter months (Luly et al., 2006). These year-round rains support perennial streams that sustain wet tropical vegetation. In contrast, the lowlands of western Cape York are strongly seasonal with regard to rain and feature vast tracts of savannah grasslands as a consequence. Rivers drain the central highlands east and west of the divide into 22 river catchments (see Figure 5, below).

Geomorphological processes have generated contrasting east-west bedrock geology and this in turn has created a biological divide (Figure 1). The eastern region bears large granite bodies and ancient upland metamorphic and igneous deposits that are incised by folds and faults that run all the way to Papua New Guinea (Willmott, 2009). The eastern tablelands have rich volcanic soils, whereas basins along the east coast consist of low-lying floodplains. The western region contains vast alluvial fans with weathered profiles of bauxite and laterite that dominate the low-lying plains (Willmott, 2009). Upland sediments are transported west along vast river, into the Gulf of Carpentaria.

1.2 | Archaeology

Debate persists as to the precise timing of human occupation of Australia, but in general terms it is considered somewhere between 68–47,000 years ago (ka BP) (Clarkson et al., 2015; Clarkson et al., 2017; Hamm et al., 2016; McDonald & Berry, 2017; O'Connell et al., 2018; O'Connell & Allen, 2004; Rasmussen et al., 2011; R. Roberts et al., 1998; R. G. Roberts, Jones, & Smith, 1990; Turney et al., 2001; Veth, 2017; Veth et al., 2017; Veth, Ditchfield, & Hook, 2014). Due to its proximity to New Guinea and Asia, Cape York is a prime candidate for the point of initial landfall and presents a suitable conduit for later movement between New Guinea and Australia (Hiscock, 2007:24, Kealy, Louys, & O'Connor, 2018; Malaspinas et al., 2016).

Although a sea barrier now exists between Cape York and New Guinea, sea level was approximately 120 m lower than present through glacial periods. This would have allowed humans and other nonvolant species to traverse the Torres Land-bridge (Willmott, 2009; D. Wright, 2011). During these glacial periods, rivers flowed from New Guinea across the Torres Land-Bridge into the Gulf of Carpentaria, which existed as a large fresh-brackish lake (Torgersen, Jones, Stephens, Searle, & Ullman, 1985). White and White (2000) have suggested that mound springs fed from the Artesian Basin may have surrounded the lake margins, creating a biodiversity hot spot and refuge for people throughout the Last Glacial Maximum.

The debate also surrounds the Melanesian influence into Australia through Cape York during the mid-late Holocene (Fitzpatrick, McNiven, Specht, & Ulm, 2018; Rowland, 2018). The presence of new technologies like the outrigger canoe (Beaton, 1985; McNiven & Ulm, 2015; McNiven et al., 2011) and the discovery of pottery on Lizard Island, south-east of the Flinders Islands (Lentfer, Felgate, Mills, & Specht, 2013) suggests that Cape York may have acted as a conduit for people moving into the continent (Rowland, 2018). The development of “increase sites” in Cape York was a spiritual/cultural aspect that may also indicate a northern connection (Hale & Tindale, 1933-34, McIntyre-Tamwoy, 2011). The development of a $^{87}Sr/^{86}Sr$ isotope reference map for the region will deliver a valuable research tool that may be applied to these questions.

1.3 | Repatriation

In the late 19th century there was a great deal of interest in the evolution of our own species (e.g. Huxley, 1863). With the discovery of *Homo erectus* in Indonesia (Dubois, 1896) a number of early researchers focused their attention on Australia and its connection with south-east Asia, considering that the region played a central role in human evolution (e.g. Klaatsch, 1923). In the absence of fossil human remains, collecting Indigenous skeletal remains for universities and museums became an activity that helped develop an understanding of modern human variability. People throughout Australia actively collected Aboriginal human remains on behalf of scientific institutions.

As Indigenous people around the world gained increased civil rights throughout the 20th Century, collecting remains for research became the focus of increased criticism. This led to the repatriation movement where Australian programs like the Return of Indigenous Cultural Property Program (2002) repatriated over 1000 sets of remains to Aboriginal communities (Berthier-Foglar, Collingwood-Whittick, & Tolazzi, 2012; Truscott, :369). However, because many of these remains were collected by lay people and government officials on the colonial frontier, they are accompanied by little contextual information. Museums and institutions have considered how to address this problem for the last 30 years. Pardoe (2013) estimated that 10–15% of the South Australian Museum's human remains collection is unprovenanced, whereas up to 25% of other Australian collections have little to no geographical contextual detail.

Cape York is one such region where the return of unprovenanced ancestral human remains is a priority for Indigenous communities. Combined with Cape York's proximity to New Guinea and Asia, and absence of modern contaminants from agriculture and development, it provides an ideal setting to test geochemical tracing techniques and measure how they are transferred through environmental proxies.

1.4 | Strontium isotope ratios

Sr is present in all rock types (clastic, metamorphic, and igneous) in form of four stable isotopes: ^{88}Sr, ^{87}Sr, ^{86}Sr, and ^{84}Sr (Faure, 1986). Sr isotope studies commonly use the ratio of the isotopes ^{87}Sr and ^{86}Sr ($^{87}Sr/^{86}Sr$). The $^{87}Sr/^{86}Sr$ ratio differs between the different rocks and minerals, depending on the amount of Sr and Rb in the minerals and their age (^{87}Sr is the daughter product of ^{87}Rb). Preferential weathering of these minerals governs what transfers into the soil. Typical labile Sr concentrations in soils range from 0.2 to 20 ppm (Åberg, Jacks, Wickman, & Hamilton, 1990; Bentley, 2006).

Soil $^{87}Sr/^{86}Sr$ is taken up by vegetation and fauna, creating a correlation between the local geology and biosphere (Kennedy, Blum, Folt, & Nislow, 2000; Koch et al., 1992). As silicates are highly weathering resistant, most Sr in soils derive from carbonates and feldspars (Capo, Stewart, & Chadwick, 1998). This bioavailable Sr fraction is further modified by hydrological, eolian, and geomorphological processes (Price, Burton, & Bentley, 2002). The bioavailable $^{87}Sr/^{86}Sr$ distribution in the landscape is established by sampling $^{87}Sr/^{86}Sr$ of different sample types. Exogenous inputs like sea spray, precipitation, dry fall as well as the role of preferential weathering, climate, ground cover, and anthropogenic disturbance all effect $^{87}Sr/^{86}Sr$ distribution (Bentley, 2006).

Sr isotopes were initially used in ecology to map the geographic movement of faunal species (Gosz, Brookins, & Moore, 1983; Koch et al., 1992; Rundel, Ehleringer, & Nagy, 1989). Because Sr is a lithophile alkaline element that is similar in size to Ca^{2+}, it substitutes Ca in calcite bearing minerals including the biogenic apatite in the mammalian body (Bentley, 2006). The large atomic mass of Sr isotopes and the small relative difference between these masses makes it less susceptible to kinetic fractionation when moving through the biosphere, making it an excellent geochemical tracer for reconstructing biological provenance (Price et al., 2002). This technique has been used to study the movement of fish (Bacon et al., 2004; Kennedy, Folt, Blum, & Chamberlain, 1997; Kennedy, Klaue, Blum, Folt, & Nislow, 2002; Walther & Thorrold, 2009), birds (Font, Nowell, Pearson, Ottley, & Willis, 2007; Sellick, Kyser, Wunder, Chipley, & Norris, 2009), extinct megafauna (Arppe, Karhu, & Vartanyan, 2009; Hoppe, 2004; Hoppe, Koch, Carlson, & Webb, 1999; Pérez-Crespo et al., 2016; Price, Meiggs, Weber, & Pike-Tay, 2017), extant herbivorous mammals (Baumann & Crowley, 2015; Britton, Grimes, Dau, & Richards, 2009; Koch et al., 1995; Sealy, van der Merwe, Sillen, Kruger, & Krueger, 1991; Widga, Walker, & Stockli, 2010), and humans (Britton et al., 2011; Copeland et al., 2011).

Ericson (1985) was the first to propose using Sr isotope ratios in human teeth and bones to look at prehistoric migration. Since then studies around the globe have utilised Sr isotope variability to understand Hominin migration and provenance (Bentley, 2006; Cox & Sealy, 1997; Ericson, 1985; Evans, Chenery, & Fitzpatrick, 2006; Ezzo, Johnson, & Price, 1997; Grupe et al., 1997; Hoogewerff et al., 2001; Juarez, 2008; Kusaka et al., 2009; Maurer et al., 2012; Montgomery, 2010; Nehlich et al., 2009; Price et al., 2002; Price, Bentley, Lüning, Gronenborn, & Wahl, 2001; Price, Grupe, & Schröter, 1994; Price, Grupe, & Schröter, 1998; Price, Manzanilla, & Middleton, 2000; Richards et al., 2008; Sealy et al., 1991; Sealy, Armstrong, & Schrire, 1995; L. E. Wright, 2005). After advancements in mass spectrometry, Sr isotope studies have become part of a package of analyses commonly conducted in archaeology. To systematically undertake provenancing, landscape Sr variability studies have been undertaken to set baselines, from which migration can be established. Regional maps of $^{87}Sr/^{86}Sr$ distributions have been completed over the past 15 years for parts of the Americas (Bataille & Bowen, 2012; Beard & Johnson, 2000; Hodell, Quinn, Brenner, & Kamenov, 2004; Laffoon, Davies, Hoogland, & Hofman, 2012; Pestle, Simonetti, & Curet, 2013), Africa (Sillen, Hall, Richardson, & Armstrong, 1998), Asia (Song, Ryu, Shin, & Lee, 2014), Europe (Evans, Montgomery, & Wildman, 2009; Evans, Montgomery, Wildman, & Boulton, 2010; Frei & Frei, 2013; Voerkelius et al., 2010; Willmes et al., 2018), and the Middle East (Hartman & Richards, 2014).

There are several ways to map bioavailable $^{87}Sr/^{86}Sr$: (a) modeling from geological data; (b) measuring the bioavailable Sr in soil, plant, and water samples; and (c) measuring signals once they are averaged in fauna and humans. Modeling involves predicting the Sr isotope ratios from the lithology, its age and the rate of weathering (Bataille & Bowen, 2012; Bataille et al., 2018; Beard & Johnson, 2000). Many unquantifiable factors contribute to the bioavailable Sr reservoir and these stochastic inputs can result in inaccurate assumptions in the model (Stewart, Capo, & Chadwick, 1998). Because geology directly influences the bioavailable Sr isotope composition, sampling within distinct lithological units is integral to understanding $^{87}Sr/^{86}Sr$ distributions. An assessment of soil, water, and vegetation gauges the movement of $^{87}Sr/^{86}Sr$ through environmental systems. Because faunal species sample multiple Sr sources they represent the bioavailable Sr pool within that species range and provide an averaged isotopic signature (Makarewicz & Sealy, 2015). Maurer et al. (2012) found that different sample types offered contrasting $^{87}Sr/^{86}Sr$ results at sample sites in Germany, with plant and water being the most reliable for provenancing human remains. These results are site specific to Europe, being influenced by domestication and agricultural practices. In places like Cape York, where agriculture and development have had less impact, a detailed assessment of sample type reliability is required.

2 | MATERIALS AND METHODS

To establish the spatial bioavailable $^{87}Sr/^{86}Sr$ signatures of Cape York samples of soil leachates, vegetation, freshwater bodies, and local mammalian fauna from all major geological units and the 22 water catchments of Cape York were analyzed and compared. Sample sites were selected according to the Geological Map of North QLD, compiled by Bain and Haipola (1997b) and the detailed surface and bedrock lithology of North QLD (Bain & Draper, 1997a) accessed through Geosciences Australia.

2.1 | Sample collection and processing

Soil, plant, and water samples were collected from distinct bedrock lithologies. The soil was collected from ~15 to 30 cm below the ground surface and aimed to sample the subsurface (B) soil horizon, in areas devoid of natural and anthropogenic disturbance. Plant samples consisted of approximately 10–20 leaves from savannah and tropical north QLD tree species including *Acacia colei*, *Corymbia intermedia*, *Eucalyptus leptophylla*, *Eucalyptus camaldulensis*, *Jagera pseudorhus*, and *Melaleuca quinquenervia*. Freshwater samples were collected from freshwater creeks and rivers within 5 km of soil and plant samples, within the same lithology. Faunal sampling targeted macropodid and wild pig teeth, collected from the carcasses of "road-kill." Global Positioning System coordinates, photographic and bedrock lithology metadata were collected at every sample site. Sample preparation and analyses were conducted in the Radiogenic Isotope Facility (RIF) at University of Queensland, St Lucia (UQ), Radio Isotope Facility, and the Research School of Earth Sciences (RSES) at the Australian National University (ANU).

Plant sample digestion followed methods in Yu, Kamber, Lawrence, Greig, and Zhao (2007). Plant samples were washed with Milli-Q ultrapure water (with resistivity of 18.2 MΩ·cm at 25°C) to remove exogenous dust and placed in 50 ml ultracleaned quartz crucibles. Samples were ashed at 450°C for 12 hr in a muffle furnace. A 10 mg aliquot was collected and digested in 2 ml 7 N double distilled nitric acid (HNO_3) for 48 hr at 140°C. The solution was then evaporated overnight at 90°C before being redissolved in 3 ml 2 N double distilled HNO_3 for column chemistry.

All soil samples were dried overnight at 60°C before being sieved through a 2 mm Endecott standard woven wire sieve. A 100 mg aliquot was leached in 4 ml ultrapure 1 M acetic acid (CH_3COOH) for 30 min before 15 min sonication. Each sample was centrifuged at 4000 rpm for 15 min before the supernatant was removed and evaporated overnight at 90°C. The sample was redissolved in 1 ml 7 N ultrapure HNO_3 and evaporated overnight at 90°C. The solute was redissolved in 2 ml 2 N ultrapure HNO_3 on a hotplate at 120°C for 2 hours.

Water samples of 20 ml were screened through a 0.2 μm syringe filter before being evaporated at 90°C in ultracleaned Teflon beakers. The remaining solute was digested in ultrapure concentrated hydrogen peroxide (H_2O_2) at 90°C. The solute was redissolved in 2 ml 2 N ultrapure HNO_3 on a hotplate at 120°C for two hours ready for column chemistry. Ion exchange chromatography was used to isolate Sr from other elements within soil, plant and water samples. Columns were filled with 3.8 ml Eichrom Sr specific resin in 1.5 N ultrapure HNO_3 and capped at either end. Columns were rinsed before samples loaded and collected with 2 N ultrapure HNO_3.

Teeth were cleaned with water and a brush to remove particulates before being cut using an Edanta diamond cutting wheel. Molars were cut from the occlusal surface to the root apices, (diagonally) distolingual-mesiobuccal. Incisors were bisected from incisal surface to apex of the root. Samples were placed with the cut surface facing up, in an aluminum holder (3.5 × 2 cm). They were mounted using "Sculpey" modelling clay so that the exposed face was parallel to the top of the container, 0.2 mm below the rim.

2.2 | Isotope measurement

Sr leached from soil, plant, and water samples were diluted in 2% ultrapure HNO_3 doped with a 10 ppb indium internal standard and screened on a Thermo X-series II quadrupole inductively coupled plasma mass spectrometer (ICP-MS) at UQ RIF Lab. Based on the screened Sr concentrations, an aliquot of each stock solution was diluted to ca. 30–40 ppb depending on the working sensitivity of the instrument (aiming for ^{88}Sr intensity of 7–8 volts), and measured for its Sr isotope compositions on a Nu Plasma HR multicollector inductively coupled plasma mass spectrometer (MC-ICP-MS). The SRM-987 standard solution was measured before and after every five unknown samples as a drift monitor. During measurement, Sr isotope data for both SRM-987 and samples were corrected for mass fractionation using the Raleigh exponential law by normalizing to $^{86}Sr/^{88}Sr = 0.1194$. The fractionation-corrected $^{87}Sr/^{86}Sr$ ratios of the samples were further corrected using standard-sample bracketing using a polynomial fit through the SRM-987 measurements by normalizing their $^{87}Sr/^{86}Sr$ values to 0.710249 to account for long-term drift. Repeated analyses of SRM-987 yielded a mean $^{87}Sr/^{86}Sr$ of 0.710249 ± 0.000015 ($n = 68$, 2σ). This measurement falls within the accepted value of 0.71025 (Faure & Mensing, 2005) and the original value of 0.71034 ± 0.00026 (Moore, Murphy, Barnes, & Paulsen, 1982). After this protocol, separate digestions of USGS rock standards BHVO-2 and BCR-2 performed by different chemists in the laboratory give long-term mean $^{87}Sr/^{86}Sr$ values of 0.70348 ± 0.000019 (2σ, $N = 14$) and 0.70502 ± 0.000019 (2σ, $N = 36$), respectively, indistinguishable from GeoReM recommended values (GeoReM, 2005). The data set was also assessed for accuracy by reproducing sample preparation, leaching, column chemistry, and analyses. Differences between these duplicates were on average <0.0155% ($n = 38$). A Wilcoxon signed rank test with continuity correction was also completed to assess the significance of similarity. Results returned a p value of (0.1274) showing that duplicates were almost identical.

Isotopic measurements of faunal teeth were conducted at the ANU RSES by multicollector inductively coupled plasma mass spectrometry (MS-ICP-MS) using laser ablation sample introduction. Samples were measured using a Finnigan MAT Neptune Varian 820. Mounted teeth were ablated using the ANU laser ablation system, which is covered in detail in S. Eggins, Grün, Pike, Shelley, and Taylor (2003), S. M. Eggins, Kinsley, and Shelley (1998) and Grün, Eggins, Kinsley, Moseley, and Sambridge (2014). This system uses a 25 × 8 mm beam exciting the laser to illuminate a rotary wheel with apertures. This aperture is projected and demagnified onto the sample surface via a long-working distance triplet lens. The excimer laser with $\lambda = 193$ nm, delivers laser fluence of 10 J/cm^2 (0.3 GW/cm^2). Tooth surface was first "cleaned" of exogenous material using a 205 μm beam and analyzed using 160 μm beam for 120 s analyses with 30 s pre- and postablation at 10 Hz. These conditions result in approximately 5 μg sample for each analysis, removing ≈ 200 nm from the surface with each pulse (Grün et al., 2014). Enamel was ablated at three locations approximately 1 mm apart.

High levels of phosphorous in hydroxyapatite ($Ca_{10}(PO4)_6(OH)_2$ in teeth can lead to an interference on mass 87 where polyatomic compounds $^{40}Ar + {}^{31}P + {}^{16}O$ and $^{40}Ca + {}^{31}P + {}^{16}O$ have been measured (Horstwood, Evans, & Montgomery, 2008; Simonetti, Buzon, & Creaser, 2008). By adding 8 cc/min nitrogen to the plasma the sample gas flow rate can be dropped, increasing the residence time of particles in the plasma, lowering oxide production that results in less interference on mass 87 (Willmes et al., 2016). Mass 71 was measured to record polyatomics $^{40}Ca + {}^{31}P$ and $^{40}Ar + {}^{31}P$ that correlate to the interference on mass 87. Rare Earth Elements (REEs) were also monitored throughout analyses to assess sample diagenesis. No samples returned high REEs.

2.3 | Data analyses

Nonparametric statistical tests were carried out using the statistical programming language R (R Core Team, 2018) and PAST (Palaeontological Statistics Software Package) Version 3.15. XY Plots were also used to compare different sample types and assess how $^{87}Sr/^{86}Sr$ is transferred from geology to hydrology and biology. In the plots a 1:1 line is shown with the 2σ range. The difference between the soil and plant samples: $\Delta SP = (soil^{87}Sr/^{86}Sr - plant^{87}Sr/^{86}Sr)/2$ was used to determine outliers with results outside the 95% interval (2σ) excluded from further analyses. To visualize $^{87}Sr/^{86}Sr$ distribution, Geopackage Maps were used. Shape Files of geological maps were supplied by the QLD Department of Natural Resources and Mines (Detailed Geology Release-March 2017). Lithological diversity was combined with $^{87}Sr/^{86}Sr$ data to create distinct isotope ranges for each unit to understand the relationship between the geology, and how this is transported into the bioavailable $^{87}Sr/^{86}Sr$ pool.

Results were also grouped by river catchments. As noted earlier, the study area contains 22 river catchments designated by the QLD Department of Environment's Science and Aquatic Conservation Assessment Reports (DES, 2018; EHP, 2012; Rollason & Howell, 2012; Figure 5) Average faunal ranges were also compiled to map fauna feeding outside of Voronoi polygon ranges and catchments. These were compiled for three macropodid and one sus species. Priddel, Shepherd, and Wellard (1988) conducted a study of over 400 kangaroos and found that 90% of red kangaroos (*M. rufus*) range within 9 km, whereas 90% of Eastern gray kangaroos (*M. giganteus*) range within 6 km from their initial sample site equating to areas of 254.5 km^2 and 113 km^2, respectively. Agile wallabies (*M. agilis*) travel far less occupying a range of 6.7 km^2 (Stirrat, 2003) Feral pigs (*S. Scrofus*) occupy ranges of about 43 km^2 (Giles, 1980; Saunders, 1988). Ranges were mapped on the figures with range measured as the radius from the sample site.

2.4 | GIS mapping

The bedrock geology was combined with $^{87}Sr/^{86}Sr$ data to create distinct isotope ranges for each lithology. Results were also grouped by catchment to view local ranges that influence faunal and water results and compared with a Voronoi diagram illustrating plant/soil $^{87}Sr/^{86}Sr$ ranges partitioned by the distance between points in a Euclidean plane. Interpolated models were used to test $^{87}Sr/^{86}Sr$ variability mapping techniques. Kriging exploits covariance as a function of the distance between measured points to predict unsampled locations (Pilz, Kazianka, & Spöck, 2008). Kriging and Voronoi maps were created in ESRI ArcMAP 10.3 to compare models and determine the most reliable predictive surface.

3 | RESULTS AND DISCUSSION

Altogether, 94 paired soil and plant, 14 water, and 21 faunal samples were used to map Cape York bioavailable $^{87}Sr/^{86}Sr$ variability. The data are shown in Figure 2 and detailed in Table S1.

3.1 | Soil and vegetation

Soil and plant Sr isotope results showed that over 90% of paired values were strongly correlated. Spearman's rank correlation coefficient returned a value of 0.9549, indicating that $^{87}Sr/^{86}Sr$ in soils is taken up by plants with little to no offset. Mean ΔSP was −0.00031622, 25th percentile: − 0.0003245 and 75th percentile as 0.0003248 (Figure 3a).

From a data set of 94 pairs of soil and plant samples, five samples were deemed outliers (Figure 3b), being outside of the 2σ band of the 188 samples (±0.0335). Four of the outliers were excluded from further analyses because the combined average would not indicate the local $^{87}Sr/^{86}Sr$ signature taken up by fauna and humans. Outlier 6 was retained because of the similarity between fauna and soil/plant results.

Many factors can lead to a discrepancy between soil and plant results from the same location, including anthropogenic, meteorological, and geological processes. Being situated in remote far north QLD, anthropogenic interference is rare, and we interpret discrepancies reflecting a disconnection between upper and lower soil horizons and vegetation utilizing subsurface water. Outliers 27 and 42 are found in high-grade metamorphic deposits in central Cape York. The topography of these central upland regions is steep with thin soil horizons and deep weathering. These factors can lead to a disconnection between strata, with plants sourcing water from the lower deposit. Outlier 49 is sourced from a marine environment and should reflect the modern marine signature (approximately 0.70920). The soil result (0.71018) is close to this signal, however, the plant result (0.71841) is elevated and all other samples, including water, upland from this site are also elevated suggesting that subsurface water is distributing a higher $^{87}Sr/^{86}Sr$ value that is being taken up by the vegetation. Outlier 20 exhibits a significant difference between plant and soil, being 0.71343/0.73257, respectively. Considering the sample site is 50 km from the neighboring lithology and within a flat landscape where no other samples show a similar result, it is considered a sampling or analytical error.

Outlier 6 is sourced from a small area of Mesoproterozoic felsic intrusive deposits outcropping at Croydon in the south of the study area. The area exhibits some of the highest recorded $^{87}Sr/^{86}Sr$ values with soil (0.79107) and plant (0.78221) both elevated. Within 5 km of the sample site the geology changes abruptly to lower $^{87}Sr/^{86}Sr$ values (0.73598). High variability in this local area may once again lead to a disconnection between the surface soils and plants accumulating high $^{87}Sr/^{86}Sr$ values from lower deposits. However, considering that the faunal sample 99 from the same site returned a distinct and high value (0.78625) between the soil and plant values indicates that the results should be included in further analyses.

A Voronoi map (Figure 4) was constructed using combined soil and plant results after outliers had been removed. The Voronoi process partitions the Euclidean plane into convex polygons that represent one sample point corresponding to a distinct $^{87}Sr/^{86}Sr$ range. This map aids visualization of $^{87}Sr/^{86}Sr$ distribution throughout Cape York covering seven categories from low values in the

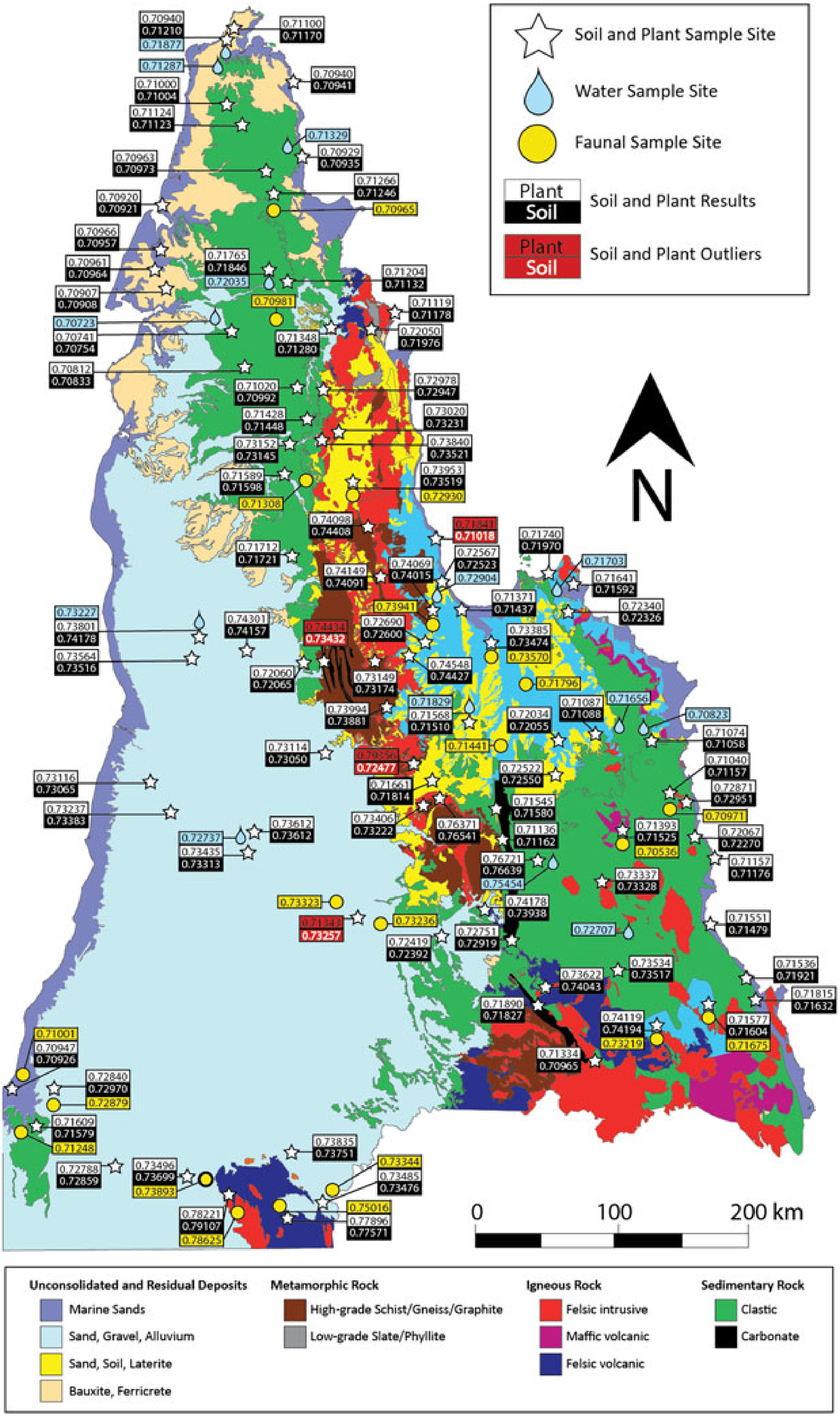

FIGURE 2 Cape York soil, plant, water, and faunal $^{87}Sr/^{86}Sr$ results on lithological map. Outliers are marked in red and discussed below [Color figure can be viewed at wileyonlinelibrary.com]

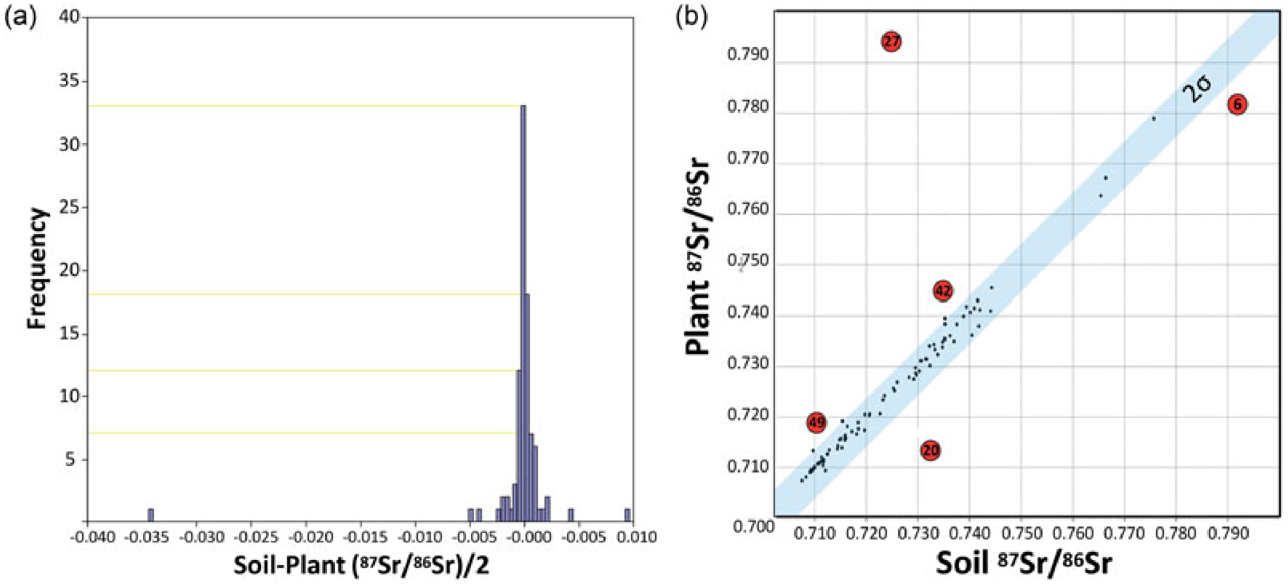

FIGURE 3 (a) ΔSP Histogram illustrating sample distribution and the five soil/plant sample outliers. Yellow lines correspond with frequency distributions of the four most common ΔSP results. (b) Soil/Plant $^{87}Sr/^{86}Sr$ results with 1:1 line and 2σ band (±0.0335). The five outliers are marked in red and discussed in the text below [Color figure can be viewed at wileyonlinelibrary.com]

north and east to high values in the central and southern regions. The map was utilized as the primary means of comparing water and faunal results to soil and plant values. The marine $^{87}Sr/^{86}Sr$ signature of approximately 0.70920 is often transported in precipitation and reflected in marine-derived rock (Bentley, 2006). These marine influences can contribute to the local bioavailable $^{87}Sr/^{86}Sr$ in soils and plants. The strong north-south gradient we see in Cape York may be due to increased marine-derived $^{87}Sr/^{86}Sr$ in precipitation and/or the local marine sandstone/limestone of the northern cape, compared with southern and inland regions. Faunal ranges were used to assess fauna feeding outside of polygon boundaries.

3.2 | Water results

Watercourses traverse geological boundaries taking on $^{87}Sr/^{86}Sr$ from weathered upland minerals in rock and soil, so catchment-wide soil results may reflect water values (Bentley, 2006). Soil results from the 22 river catchments in Cape York (Figure 5) were collated and compared with fresh water results to assess whether the local soil $^{87}Sr/^{86}Sr$ value or the catchment-wide soil $^{87}Sr/^{86}Sr$ signature had a greater effect on water results (Supporting Information Data S3).

In 14 of the catchment's sample frequency was too low for comparison so they were combined with adjacent catchments with similar values (Coleman-Holroyd, Daintree-Endeavour-Jeannie, Embley-Wentlock, Jardine-Ducie, Mossman-Barron, Lockhart-Stewart-Olive/Pascoe). The Staaten river catchment contained no samples and was, thus, excluded.

Figure 6 shows that water sample (126) falls outside the catchment range and 2σ band (±0.029), calculated from the 14 water results. While samples 120, 121, and 129 only just reach the 2σ band and could also be classed as outliers. Water-value means were evenly distributed with seven values above and below the catchment range. The Voronoi map ranges were also used to compare local soil results with corresponding water values and illustrated four samples outside the 2σ band (±0.029), with two below (117, 118) and two above (126, 128; Figure 7).

Catchment soil ranges are larger than the local Voronoi ranges, making them less accurate. Mean values were compared using analysis of variance and between the sum of squares (SSB) to test the accuracy of the two approaches. SSB results illustrated that Voronoi range mean values (presented as circles on Figures 6,7) exhibited a closer correlation with water values at 3.622E-05 when compared with catchment SSB at 8.921E-05. This result also suggests that local soil values more accurately express water values than catchment wide ranges. Considering that catchments incorporate many lithologies, with seasonally fluctuating mineral weathering sourced only from upstream, this result is not surprising.

3.3 | Faunal results

Twenty-one faunal results were compared with soil and plant results within the species foraging territory, to assess the reliability of utilizing local soil and plant samples for predicting mammal $^{87}Sr/^{86}Sr$ values (Supporting Information Data S2). Maximum faunal ranges were calculated for three macropodid and one sus species, indicating that seven faunal samples were collected with species range overlapping polygon borders. These species habitats are presented as $^{87}Sr/^{86}Sr$ ranges in Figure 8 and indicate that 80% of faunal results fall within the measured local $^{87}Sr/^{86}Sr$ range for soil and plant results. Mean faunal $^{87}Sr/^{86}Sr$ results were also compared with combined soil and plant mean results using analysis of variance to assess the similarity between the datasets. The between SSB was

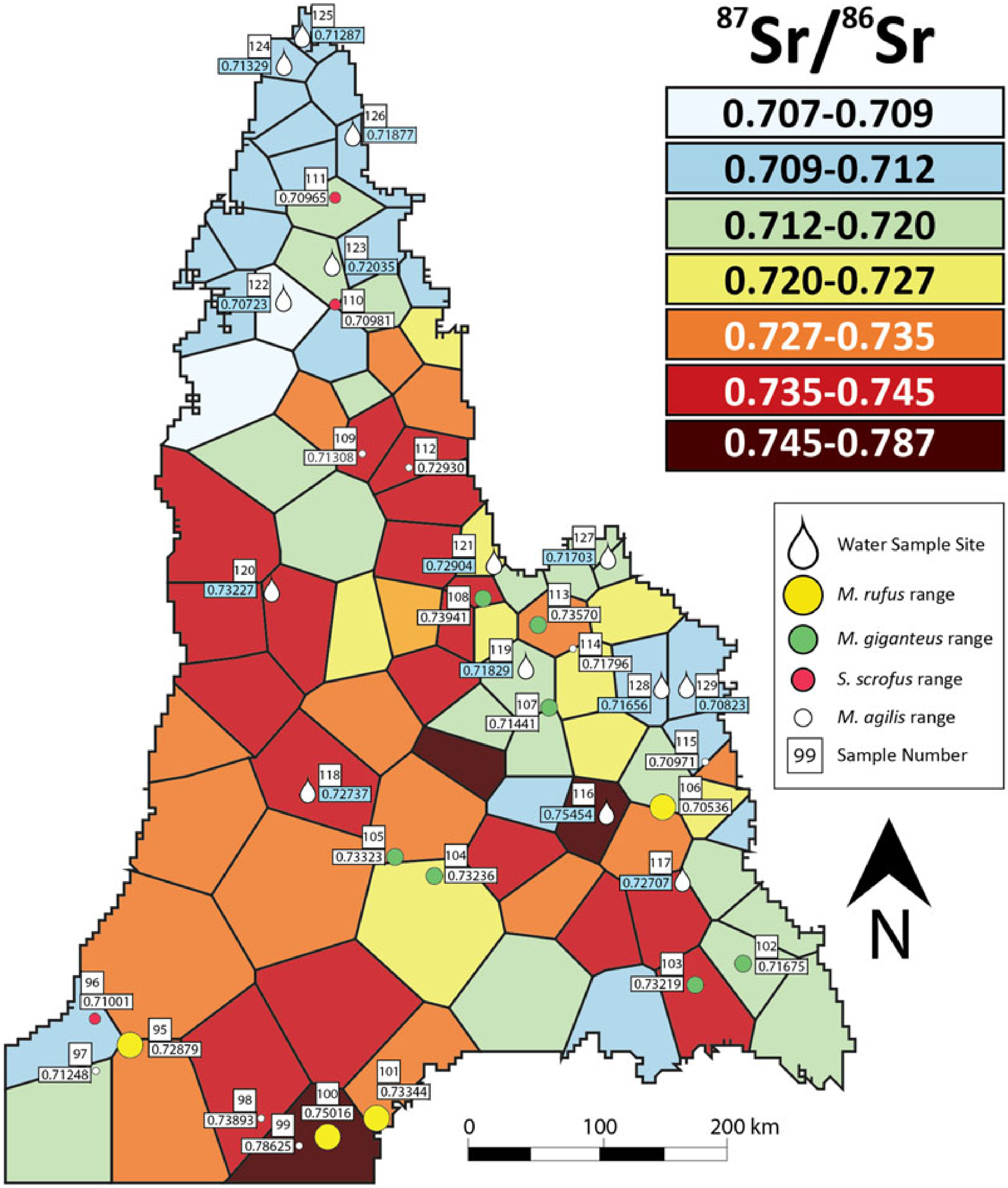

FIGURE 4 Voronoi diagram of combined soil/plant $^{87}Sr/^{86}Sr$ ratio ranges throughout Cape York, Australia. The figure includes water and faunal results with typical faunal habitat ranges [Color figure can be viewed at wileyonlinelibrary.com]

0.000147, indicating a strong association between soil/plant and faunal values. Results suggest that soil and plant samples are a reliable proxy for estimating local mammal $^{87}Sr/^{86}Sr$ values. Water results were unable to be compared with faunal results due to sample density and a lack of water and faunal results in the same vicinity. However, because local soil and plant results have been shown to correlate with both water and faunal results accurately, and because local results are more indicative of water results when compared with catchment wide signatures, we consider water values within species range a valid mammalian body tissue $^{87}Sr/^{86}Sr$ input.

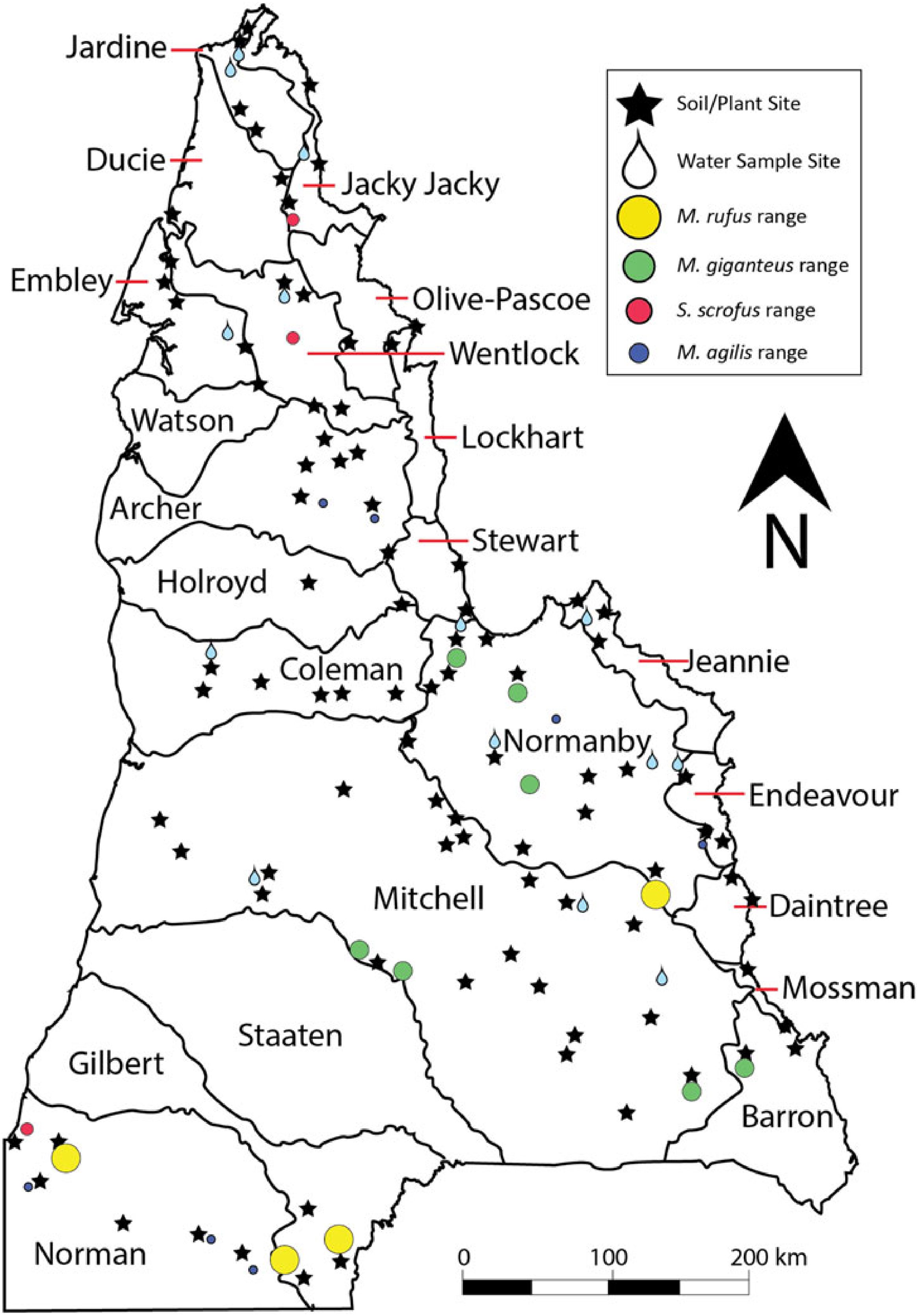

FIGURE 5 Cape York river catchments with typical faunal habitat ranges represented by spot size (EHP, 2012; DES, 2018; Rollason & Howell, 2012) [Color figure can be viewed at wileyonlinelibrary.com]

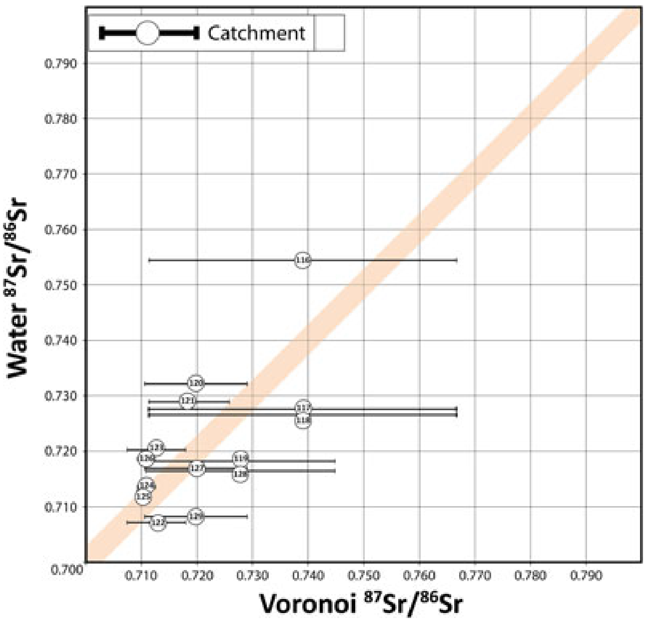

FIGURE 6 Water $^{87}Sr/^{86}Sr$ results compared with catchment soil ranges with a 2σ band (±0.029) [Color figure can be viewed at wileyonlinelibrary.com]

Figure 8 also shows that four of the faunal samples (104, 106, 109, and 112) sit outside the 2σ band (±0.033), calculated from the 21 faunal results. Outliers 104 and 109 are within 20 km of polygons that reflect their results, and it is possible that the Voronoi polygon boundaries in this region do not accurately display the local $^{87}Sr/^{86}Sr$ gradient between sample sites. The plot also displays most of the faunal result means below the 2σ band. The marine $^{87}Sr/^{86}Sr$ signature of approximately 0.70920 can be transported in precipitation (Bentley, 2006) and will dictate the $^{87}Sr/^{86}Sr$ value in surface runoff, potentially disconnecting it from the local soil signature. Although macropodid species have lower mean turnover rates of water per day than eutherian species, they will still drink surface water, and during monsoonal seasons surface runoff would likely incorporate a large portion of daily water intake (Denny & Dawson, 1975). It is possible that Cape York surface runoff during the monsoon season is influenced by a marine signal in precipitation contributing to faunal body water $^{87}Sr/^{86}Sr$. This exogenous input would present faunal $^{87}Sr/^{86}Sr$ signatures generally lower than the local soil value. This would also explain why outlier 112 close to the coast is lower than the surrounding soil and plant values. Sample 106 is an anomaly as it represents the lowest value in the data set. This red kangaroo (*M. rufus*) was sampled on a major road to the south and the species is not generally recorded this far north, suggesting that it may have covered a distance in excess of 100 km and perhaps represents $^{87}Sr/^{86}Sr$ values from outside of the study area.

3.4 | Cape York geological $^{87}Sr/^{86}Sr$ results

Whether it be bedrock or a combination of weathered substrates and minerals, geology is the dominant driver of the spatial distribution of $^{87}Sr/^{86}Sr$. Regional studies have consistently demonstrated that the young volcanic and limestone's islands of south-east Asia, Melanesia, and Oceania exhibit $^{87}Sr/^{86}Sr$ results below the modern marine value of approximately 0.70920 (Bentley et al., 2007; Cheung, Burley, Phaff, & Richards, 2018; Fenner, Gagan, Cowley, Armstrong, & Prasetyo, 2016; Kinaston et al., 2014; B. Shaw, Buckley, Summerhayes, Stirling, & Reid, 2011; B. Shaw et al., 2010; B. J. Shaw, Summerhayes, Buckley, & Baker, 2009; Theden-Ringl, Fenner, Wesley, & Lamilami, 2011).

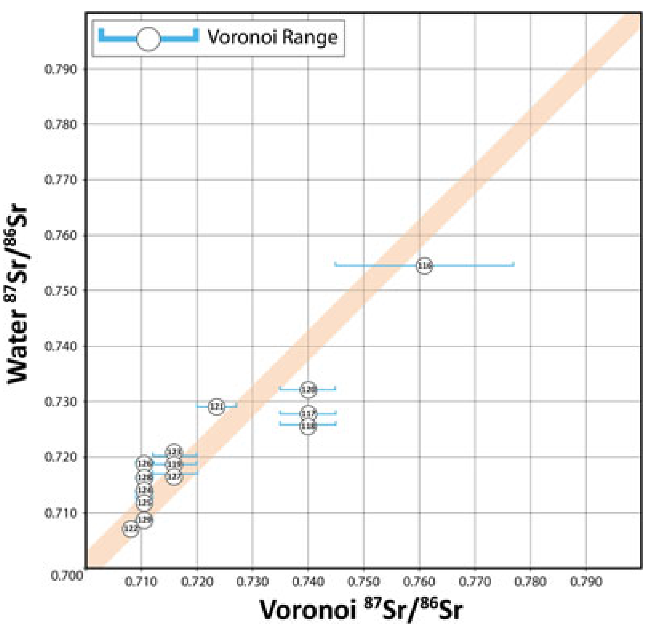

FIGURE 7 Water $^{87}Sr/^{86}Sr$ results compared with local soil ranges with a 2σ band (±0.029) [Color figure can be viewed at wileyonlinelibrary.com]

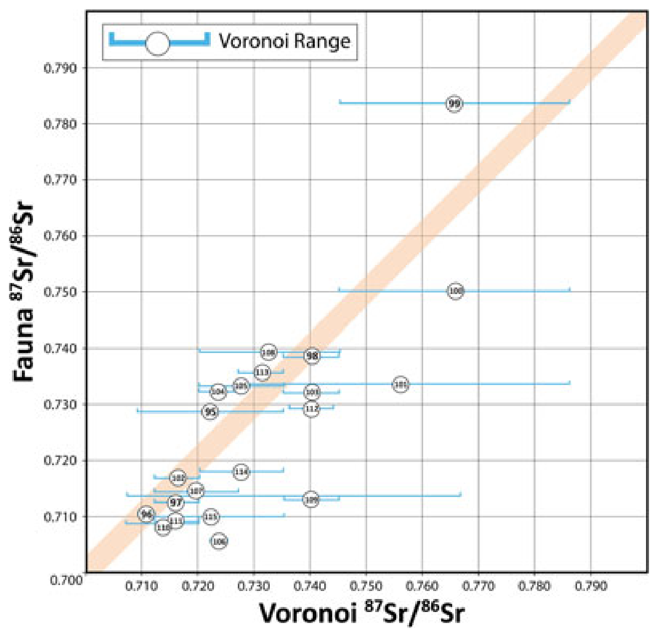

FIGURE 8 Faunal $^{87}Sr/^{86}Sr$ results compared with combined soil and plant Voronoi ranges that take into account faunal feeding range with a 2σ band (±0.033) [Color figure can be viewed at wileyonlinelibrary.com]

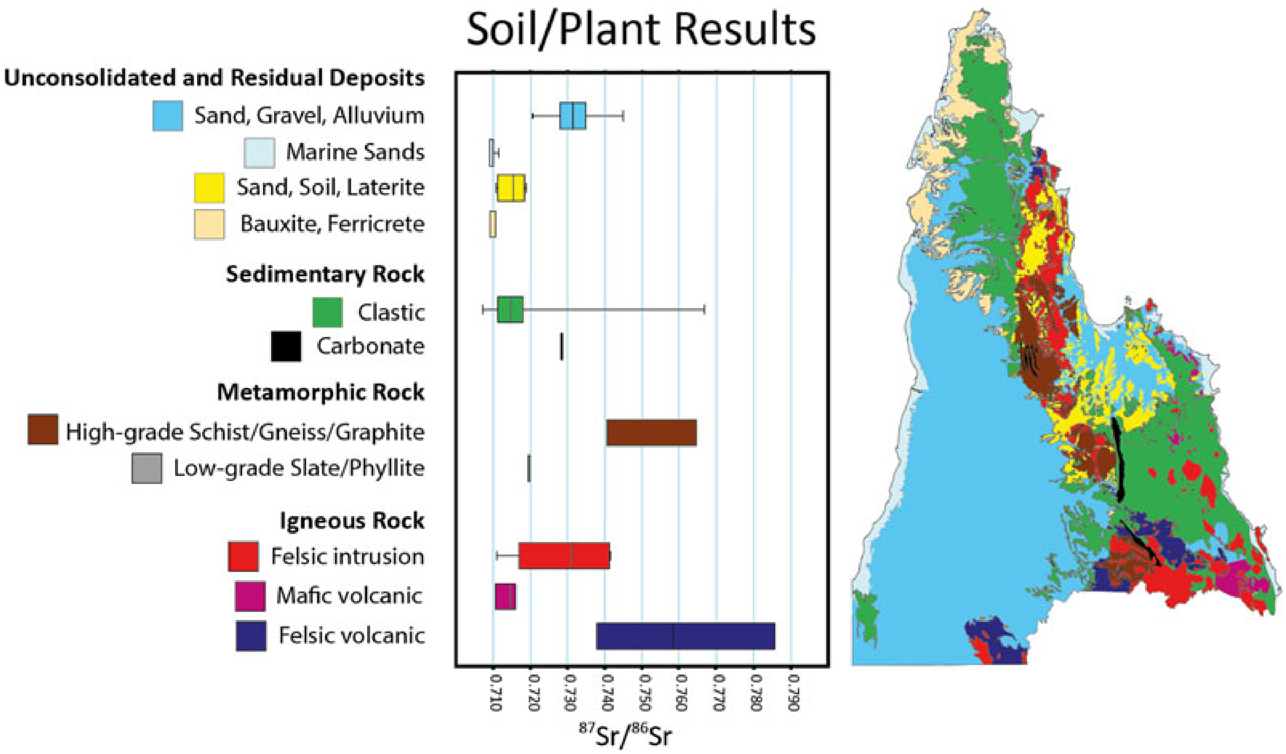

FIGURE 9 Cape York soil and plant results aligned to rock types, with outliers excluded. Boxplot colors represent rock types on the lithological map [Color figure can be viewed at wileyonlinelibrary.com]

Cape York soil and plant results reflect parent lithologies and results were grouped by their underlying bedrock to understand how lithological type and age contributed to results. Figure 9 presents Cape York $^{87}Sr/^{86}Sr$ ranges by lithological type, indicating the highest values occur in regions overlying felsic volcanic rock and high-grade metamorphics. If outliers indicated by whiskers are discounted we can attribute $^{87}Sr/^{86}Sr$ ranges to distinct lithologies. Values of ≤0.71000 only occur in marine sands (reflecting the marine $^{87}Sr/^{86}Sr$ signature) and bauxite/ferricretes. $^{87}Sr/^{86}Sr$ ratios between 0.71000 and 0.71700 are found in mafic volcanic regions, as well as the widely distributed consolidated and unconsolidated clastic sediments of the eastern half of Cape York. Values between 0.71700 and 0.73800 are found in small pockets of slate and carbonates as well as in the felsic intrusions and widely distributed sands and gravels of the south-western half of Cape York. $^{87}Sr/^{86}Sr$ values between 0.74000 and 0.76500 are only found in high-grade schists and gneisses as well as felsic volcanic rocks, the highest values of ≥0.76500 are only found in the latter. $^{87}Sr/^{86}Sr$ results classified by lithological units are presented below and in Supporting Information Data S4 (Figure 13).

3.4.1 | Igneous rocks

Felsic intrusive

Devonian–Carboniferous igneous felsic rock that is largely composed of adamellite and granite runs through much of eastern Cape York (Willmott, 2009). They have become prominent landmarks along the east coast due to their resilience to weathering. Erosion of the overlying rock has exposed these granites, that exhibit a $^{87}Sr/^{86}Sr$ range of 0.71100–0.74253 (14, 39, 41, 50, 53, 54, 55, 77, 78, 84, and 90).

Mafic volcanics

Some of the lowest $^{87}Sr/^{86}Sr$ values recorded in this study were measured in rock formed from basaltic magmas that outcrop along the mid-east coast. These were generated by partial melting at mantle depths and decompression of a rising plume. They ascended to the earth's surface and erupting to form alkali basalt basanite and hawailite compositions. This domed-up the eastern portion of the continent before vast sections sank (Willmott, 2009). Basalts generally exhibit low $^{87}Sr/^{86}Sr$ values and here they express a range of 0.71065–0.71591 (12, 36, 89).

Felsic volcanics

Igneous felsic volcanic rock from the Mesoproterozoic is found in the middle of southern Cape York and returned the highest combined soil/plant result for the study at 0.78664 (6). Cape York also witnessed volcanic activity through the Cainozoic. These areas exhibit a restricted and lower $^{87}Sr/^{86}Sr$ range of 0.73833–0.74156 (13, 16)

3.4.2 | Metamorphic rocks

High grade metamorphics

Cape York contains several inliers that are considered to be part of a sequence deposited on a rise during the Proterozoic (I. Withnall, Bain, Draper, MacKenzie, & Oversby, 1988). The rock today consists largely of metamorphic mica-quartz schist, quartzite, and biotite-feldspar-quartz gneiss dating from the Palaeoproterozoic to the Mesoproterozoic. This lithology returned high results at 0.74058 – 0.77733 (7, 18, 27, 29, and 42).

Low grade metamorphics

Mica and schists were formed from the volcanic and sedimentary rocks on the eastern edge of the ancient super-continent "Pangea." Here they metamorphosed and later outcropped along the mid-east coast (Blewett & Black, 1998). These metamorphics are easily weathered soft schists and mica with some quartzite (Willmott, 2009). The lithology is represented by only one sample exhibiting a low $^{87}Sr/^{86}Sr$ result of 0.72013 (75).

3.4.3 | Sedimentary rock

Clastic sediments

Clastic rocks are a mixture of old and young lithologies that have weathered and been reformed. It is this mixing of many different lithologies that gives clastic rock such a wide range of values (0.70747–0.76680). High $^{87}Sr/^{86}Sr$ values are associated with Palaeozoic clastic rocks and metasediments throughout the south-central region of the cape, returning $^{87}Sr/^{86}Sr$ values up to 0.76680 (33). However, the same lithology throughout south-east Cape York also expresses low values: 0.71167–0.73525 (10, 11, 15, 35, 85, 91, 92, 93, 94).

Clastic material formed from weathered upland sediments, with ages between 160 to 95 Ma, cover vast areas of Cape York (Willmott, 2009). Quartzose sandstones and siltstones now occupy the tip of the cape and regions in the central-east, exhibiting a low $^{87}Sr/^{86}Sr$ range of 0.70968–0.71314 (62, 64, 69, and 74). While basins of calcareous claystone and glauconitic sandstones are a remnant of marine transgression and occupy the entire western flank of Cape York (I. W. Withnall & Cranfield, 2013). These western basins returned the lowest $^{87}Sr/^{86}Sr$ result in the study 0.70747–0.72386 (3, 19, 43, 52, 56, 57, 58, 59, 60, 61, 73, 79).

Running north-south through the center of the cape is a strip of mudstone, siltstone, and sandstone that abuts marine material laid down in the Silurian Devonian (Illig & Chang, 2016). The region comprises of fossiliferous mudstone, chert, sandstone, and basalts that exhibit a low $^{87}Sr/^{86}Sr$ range of 0.71148–0.71563 (31, 32).

Carbonates

Represented by only one combined soil/plant sample this lithology in south-central Cape York separates clastic Devonian rock from high-grade metamorphics (Illig & Chang, 2016). This narrow stretch of shallow marine limestone, sandstone, and basalt exhibits a $^{87}Sr/^{86}Sr$ value of 0.72835 (17).

3.4.4 | Unconsolidated and residual deposits

Residual/Colluvial

Much of the north-western regions of Cape York contain bauxite and ferricrete residuals and colluvium. These lithologies are residual deposits that are situated very close to the coast and exhibit a strong marine signature of approximately 0.70920. Being material eroded from Jurassic–Cretaceous alluvial sediments, $^{87}Sr/^{86}Sr$ results range from 0.70908–0.71737 (30, 38, 65, 66, 68, 71, 72, 81, and 88).

Alluvial

Around 95 MYA seas that covered much of Cape York receded exposing rock formed during the Jurassic–Cretaceous. These sediments eroded into vast alluvial fans along the east and western lowlands of Cape York (Doutch, 1976). From the Miocene to the Pliocene, alluvial material was also deposited along these coastal margins. The western basins exhibit a $^{87}Sr/^{86}Sr$ range of 0.72707–0.74229 (1, 4, 5, 8, 9, 20, 21, 22, 23, 24, 25, 26, 28, 34, 44, 45, 46, and 51). While the eastern lowland basins exhibit a wider $^{87}Sr/^{86}Sr$ range of 0.71796–0.74488 (37, 40, 47, 48, 80, 82, 86, 87). These $^{87}Sr/^{86}Sr$ results are diverse because they are a culmination of weathered biproducts from Precambrian rock, Palaeozoic clastic, and Devonian igneous felsic material.

Marine sands

Areas along the coast naturally exhibit results close to the modern marine signature (approximately 0.70920). These dune fields and areas of seawater inundation exhibit a $^{87}Sr/^{86}Sr$ range of 0.70920–0.71148 (2, 63, 67, 70, 76).

3.5 | $^{87}Sr/^{86}Sr$ mapping and sampling

Interpolation models have been used to map bioavailable $^{87}Sr/^{86}Sr$ in Europe (Willmes et al., 2018) and was carried out on Cape York soil, plant and water results. Parameters were compared across three kriging interpolation methods: simple, Empirical Bayesian Kriging and Cokriging (Figures 10–12, Figure 13)

Simple Kriging data were log transformed and a nugget utilized in the covariogram. Neighbors were set at a maximum of 15, and a minimum of five over eight sectors with standard neighborhood type (Figure 10a). The combined data set was also run using the Empirical Bayesian Kriging (EBK) function set at 200 simulations with nugget enabled (Figure 11a). Data were analyzed using a power semivariogram with a maximum of 15 neighbors and a minimum of 10 over eight sectors with standard neighborhood type. The data set was also visualized using the cokriging function that not only analyzed the soil/plant data set using autocorrelation but also cross-correlated between the soil/plant, water, and faunal datasets (Figure 12a). All datasets were log transformed and simple type kriging used. By removing the nugget and using the K-Bessel model type best visual fit of the covariogram was achieved. This model showed the best overall results for regression function and the predictive mean was assessed to be 0.0005561, thus allowing the data to sit close to the observed values. The cokriged surface was determined to be the most reliable surface for predicting values at unknown sample types because it honored the heterogeneity of the data set better than other methods. Although error surfaces for simple and EBK interpolated surfaces (Figures 10,11) suggest lower error margins than the cokriged surface (Figure 12b), heterogeneity in the data set

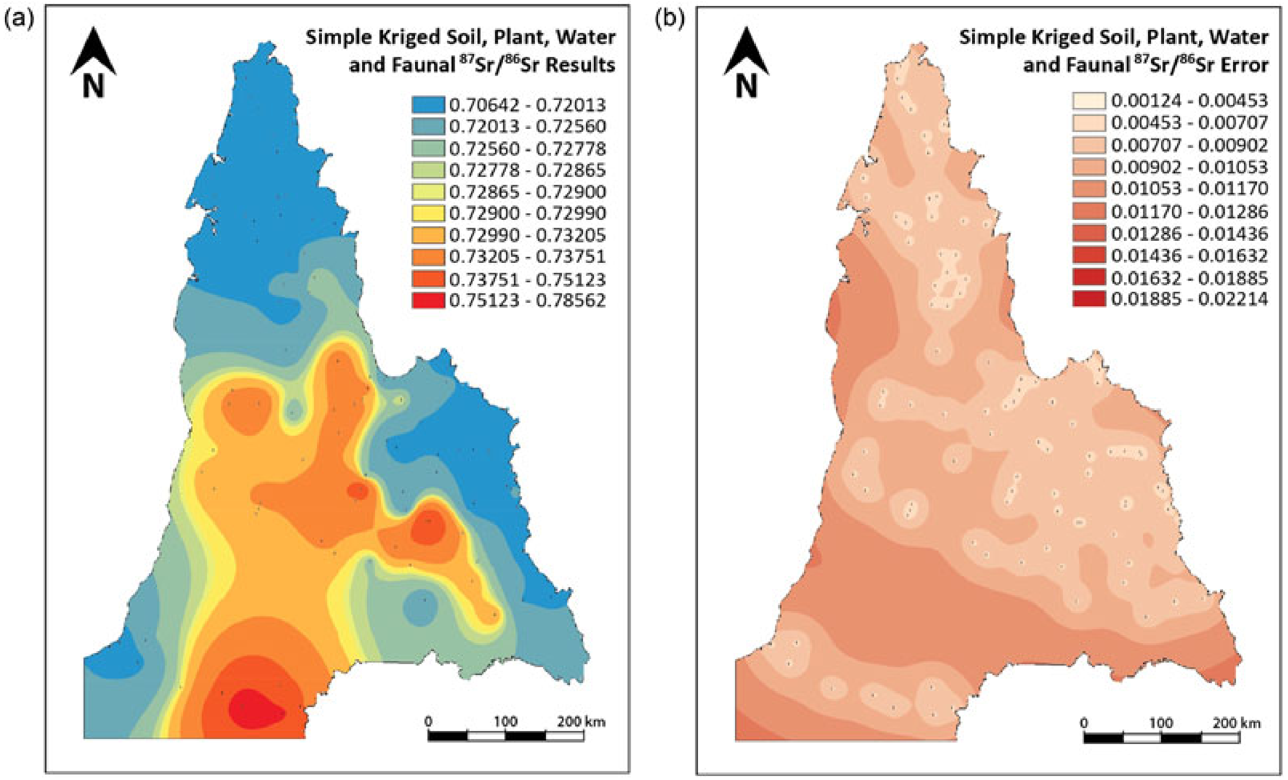

FIGURE 10 (a) Cape York combined soil, plant, water, and faunal simple kriged surface. (b) Combined soil, plant, water, and faunal simple kriged error surface [Color figure can be viewed at wileyonlinelibrary.com]

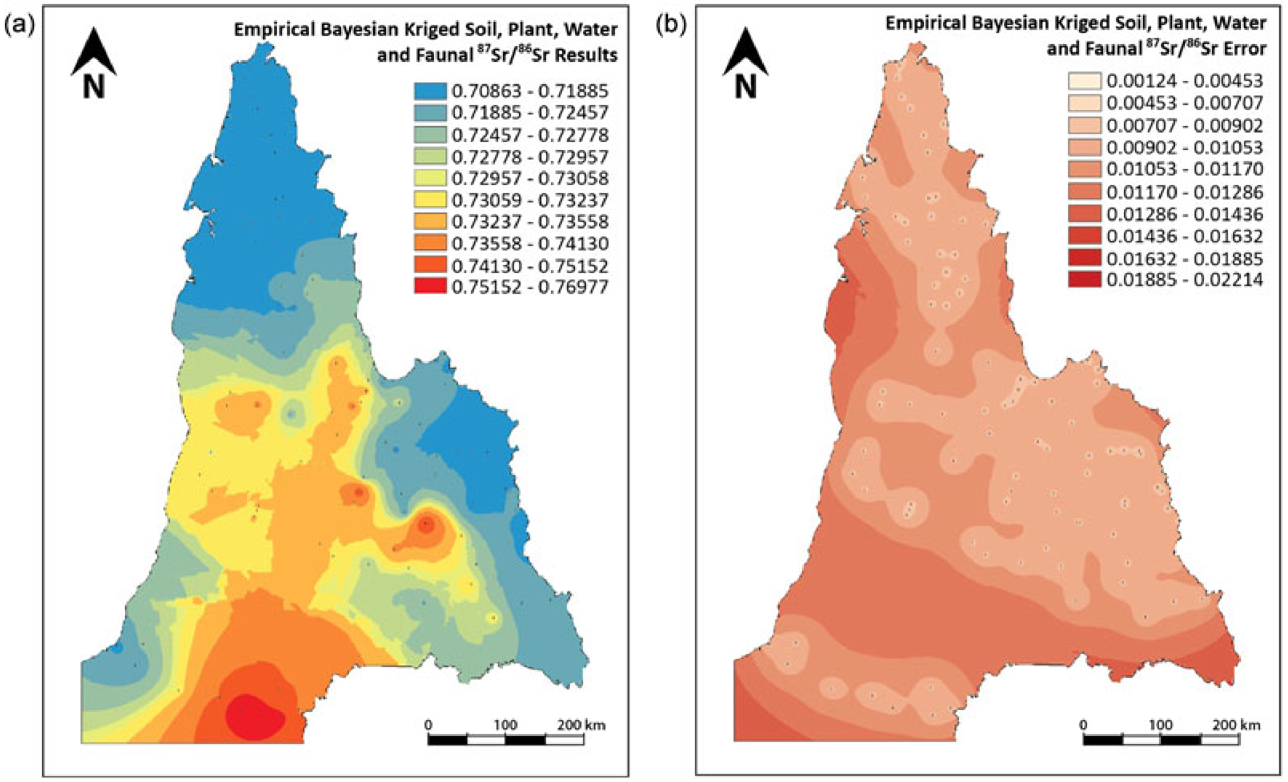

FIGURE 11 (a) Cape York combined soil, plant, water and faunal EBK surface. (b) Combined soil, plant, water, and faunal EBK error surface. EBK, Empirical Bayesian Kriging [Color figure can be viewed at wileyonlinelibrary.com]

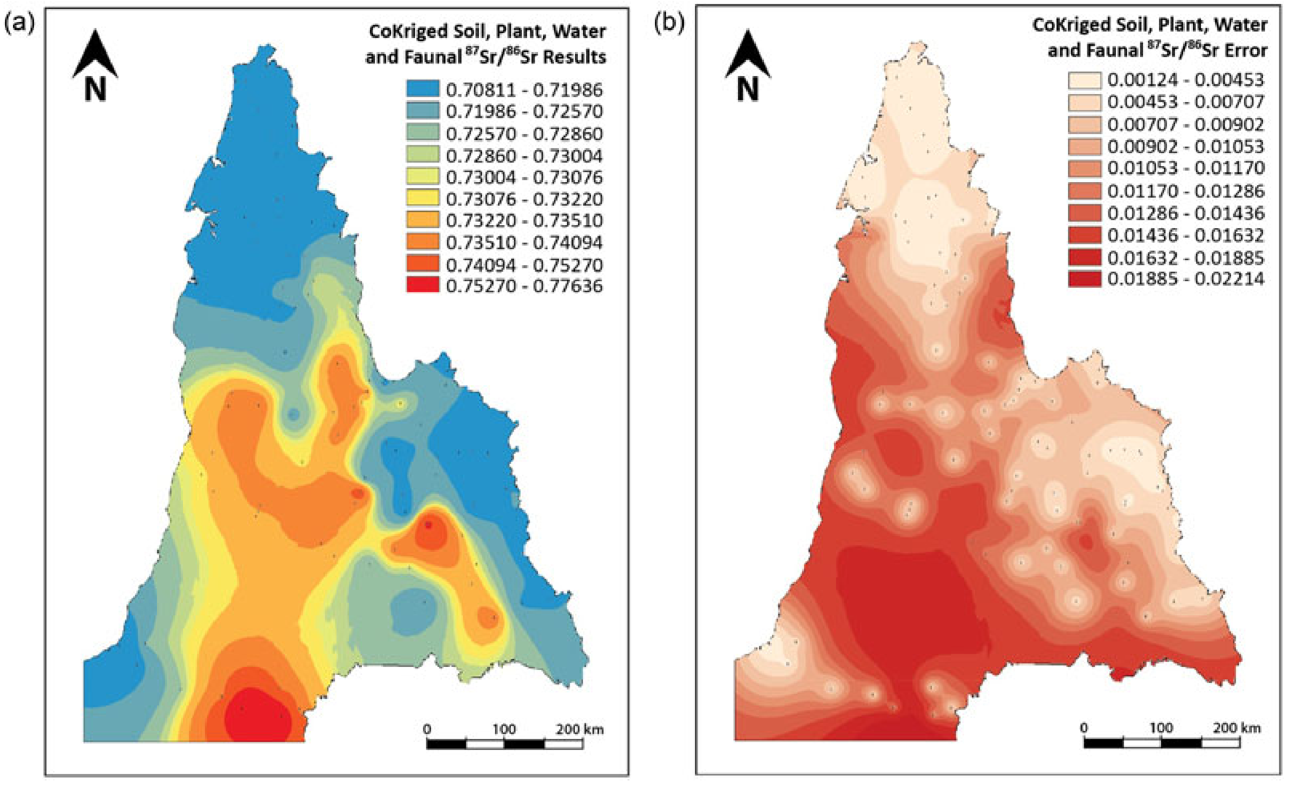

FIGURE 12 (a) Cape York combined soil, plant, water and faunal cokriged surface. (b) Combined soil, plant, water, and faunal cokriged error surface [Color figure can be viewed at wileyonlinelibrary.com]

has been killed and ranges do not reliably adhere to local $^{87}Sr/^{86}Sr$ results.

Interpolation requires spatial autocorrelation that assesses whether samples close together are more similar than samples further apart (Gunarathna, Kumari, & Nirmanee, 2016). In geology we see lithologies with high $^{87}Sr/^{86}Sr$ values abutting lithologies of low $^{87}Sr/^{86}Sr$ values, defying the law of spatial autocorrelation. Therefore, interpolated models smooth the data and heterogeneity can often be lost. Because of this process, all three interpolated surfaces (Figures 10–12) have distinct $^{87}Sr/^{86}Sr$ ranges due to the utilization of different model parameters on the same data set.

By way of comparison, we can view the data as a Voronoi map, which offers a distinct value associated with each sample (Figure 4). This map more accurately represents the heterogeneity of soil/plant results and illustrates the degree of variability on the northern cape, that is excluded in all interpolated models. However, the Voronoi process also depends on sample distribution and Figure 4 illustrates that the under-sampled regions of south-western Cape York are presented as uniform, when in fact this is due to a lack of sampling. To this extent, both techniques have their downfalls and both make assumptions about $^{87}Sr/^{86}Sr$ range and heterogeneity depending on sampling density and variability. Ultimately it falls to the user of these surfaces to discern what is the most appropriate for their purpose and it would be irresponsible to suggest that either of these surfaces is foolproof for predicting human values. We would argue that a combination of surfaces should be used to understand regional $^{87}Sr/^{86}Sr$ distribution.

The goal of this study was to design a system and mapping protocol that can be used to understand human migration, provenance, and aid in repatriation efforts. We find that soil, plant, water, and faunal results all offer a means of assessing local $^{87}Sr/^{86}Sr$ variability that can be used to map distribution. Maurer et al. (2012) measured how reliably different sample types represented $^{87}Sr/^{86}Sr$ results in German archaeological remains. Their results indicated that anthropogenic interference from chemical fertilizers contaminated soil and faunal samples and they concluded that water and vegetation offered the most reliable method for developing $^{87}Sr/^{86}Sr$ baselines for investigating past human migration in Germany. Our study was carried out in remote north-east Australia where agricultural practices are a modern phenomenon. Aside from pastoral activities, the region is largely undeveloped and the potential for modern anthropogenic interference is low. Our results indicate that Cape York plant $^{87}Sr/^{86}Sr$ is almost identical to soil leachate $^{87}Sr/^{86}Sr$ and, when combined, they are a reliable indicator of bioavailable $^{87}Sr/^{86}Sr$ that is transferred into water and fauna. Water and faunal samples have been shown to closely align with local soil and vegetation results, even after lithological and environmental processes are taken into account. We would argue that in remote areas devoid of modern contaminants, the most reliable method of measuring Sr isotope distribution is by utilising soil and plant results. By first measuring $^{87}Sr/^{86}Sr$ in soil and plants, weathering processes and exogenous inputs can be assessed. Because humans also sample fauna and water from a given territory their inclusion in a study is important but, as we have shown above, soil and plant results are a valid representation of the locally

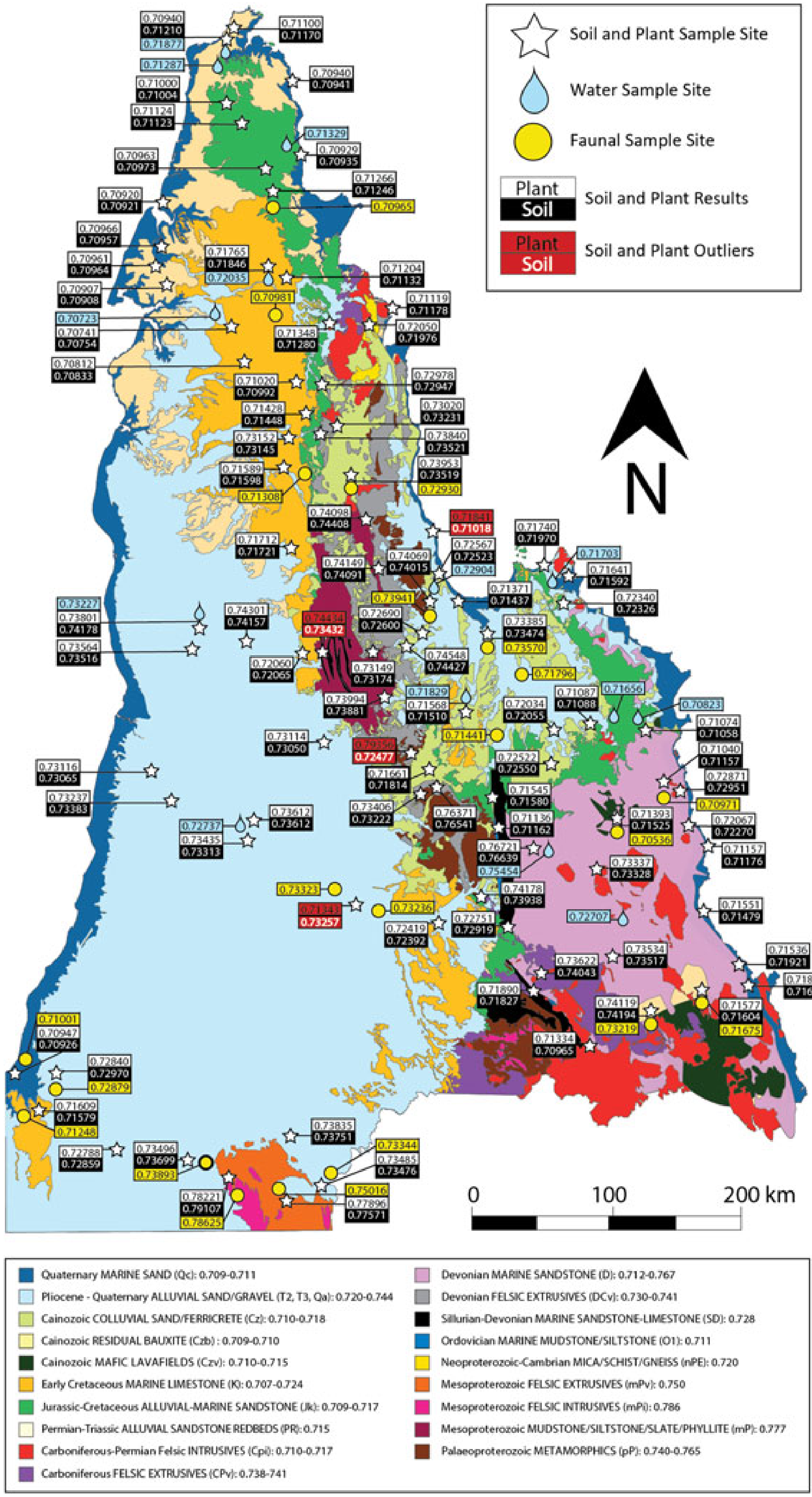

FIGURE 13 Cape York $^{87}Sr/^{86}Sr$ results on a lithological map (Bain & Haipola, 1997b) [Color figure can be viewed at wileyonlinelibrary.com]

weathered bioavailable $^{87}Sr/^{86}Sr$ and a reliable indicator of what should be found in other sample types.

4 | CONCLUSION

This project is the first to map regional $^{87}Sr/^{86}Sr$ distribution in Australia that can be used to provenance human remains and other biological material. $^{87}Sr/^{86}Sr$ distribution was found to be dependent on geological and environmental factors with outcropping ancient metamorphosed Precambrian material returning extremely high values, presenting a combined $^{87}Sr/^{86}Sr$ range of 0.70536–0.79356. We have demonstrated that surface soil and plant results are a reliable indicator of local $^{87}Sr/^{86}Sr$ expressed in the biology and hydrology. The similarity between soil, plant, water, and faunal results attests to the power of using radiogenic isotopes like Sr for provenance studies and the combination of all four sample types amplifies the reliability of predicting human provenance. In the absence of a suite of sample types, soil and plant results offer the most accurate technique for assessing regional Sr isotope variability. Although geostatistical models are commonly used to predict values at unsampled locations, we found that the methods we used were not a robust technique for mapping Sr isotope variability in Cape York. We believe unmodelled data represented the heterogeneity of geology more accurately in north-east Australia and should be assessed primarily to assign provenance in the region. Results from this study may aid in establishing the provenance of skeletal remains held in institutions that hold no geographical contextual detail and contribute to a more nuanced understanding of prehistoric human mobility in Australia.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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