PROCEEDINGS OF THE ROYAL SOCIETY OF QUEENSLAND

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VOLUME 131

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PROCEEDINGS OF THE ROYAL SOCIETY OF QUEENSLAND

Editor: Justyna Miszkiewicz

Special thanks are extended to the referees who reviewed papers submitted for publication in this volume of the *Proceedings*.

2022

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COVER ILLUSTRATION
Image showing the peak of Mount Lindesay, mountain located on the border of Queensland and New South Wales (Credit: Paul Williams). On pages 51–61, Williams et al. evaluate the role of planned burning on subtropical eucalypt forest following the 2019 wildfire at Mount Lindesay.

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EDITORIAL FOREWORD

It has been a pleasure editing the 131st volume of the *Proceedings of The Royal Society of Queensland*. The breadth and depth of Queensland research published in the volume highlights the fact that the boundary between domestic and international research significance is blurred. We have novel results presented for disciplines such as geology, public health, biodiversity conservation, ecology, and history of science, to name a few. These contribute to the global progress of science and further our understanding of emergencies such as climate change and socio-geographical inequalities in health. It is paramount that scientific journals rely on rigorous peer review to publish high-quality data and evidence in the face of an increasingly post-truth world. I am pleased that the publication success rate for Volume 131 is 70%, reflecting the great calibre of submitted papers, but also our commitment to high editorial standards.

Burndred and Sternberg document biological responses of the endangered Cooper Creek catfish (*Neosiluroides cooperensis*) to environmental threats aiding in conservation planning for this species. Using new insights from field-based mapping, Perkins re-interprets the geology of the Kalkadoon/Leichhardt Complex and the Magna Lynn Metabasalt. Parayiwa et al. conduct a space-time analysis of 2008–2018 records of perinatal health across Queensland to find high rates of low birthweight in populations living in Far North Queensland. In two articles led by Williams, Brisbane eucalypt forest flora response to fire and the role of planned burning on subtropical eucalypt forest at Mt Lindesay are evaluated, helping us better understand the resilience of forest ecosystems.

In the review article series, Lloyd and George tackle issues with climate change scepticism in the rangelands by offering a series of strategies to better transfer knowledge to producers and other stakeholders. Dart et al. highlight the seriousness of the effects of coal seam gas mining and its lack of regulation on agricultural land in the Darling Downs. In another article, Dart et al. offer alternative means for protecting biodiversity on privately tenured rural land and assess the strengths and weaknesses of current approaches in Australia, including those by the Queensland Government. Rix sheds light on the palaeontological significance of the Redback Plains Formation and highlights the need to better protect fossil sites in Queensland and Australia.

The future of science is in the hands of Early-career Researchers (ECR) who face unprecedented challenges in accessing research funding. I am thrilled that we were able to give ECRs from across Queensland a platform to showcase their research at our event held in early 2022. Selected abstracts from this event are featured in a dedicated section of the volume, where preliminary findings on a range of topics are presented including breeding for disease-resistant strawberries (O'Connor et al.) and mathematical modelling for improving coral aquaculture (Lippmann et al.). A collaboration between Griffith University and Indigenous researchers combining archaeological science with Traditional knowledge is revealing complex functions of boomerangs (Martellotta & Craft).

The Presidential Address 2022 reflects on limited global and local progress towards sustainability. I am inspired by the 'Doughnut' model, which I hope will guide populations to a better future. Finally, it is an honour to feature Angela Arthington's career retrospective accompanying her citation in recognition of her career. She is a world-renowned figure in freshwater biodiversity – we are lucky to have her here in Queensland.

Producing this volume was a team effort and so I extend huge thanks to Darryl Nixon from Sunset Publishing Services Pty Ltd., John Tennock, James Hansen, Geoff Edwards, Julien Louys, and all the peer reviewers. Thank you to the Society members, and the Council of The Royal Society of Queensland, for warmly welcoming me to our community and giving me the opportunity to edit the volume.

Justyna J. Miszkiewicz
Editor, PRSQ Volume 131, 2022

The Royal Society of Queensland acknowledges the Iningai Nation, their long custodianship and inherent connection to country, its springs and waterways, plants and animals. We pay respect to the knowledge and cultural values of First Peoples of Australia and acknowledge Elders past, present and future.

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Refereed Papers

Biology and Reproductive Ecology of the Endangered Cooper Creek Catfish (*Neosiluroides cooperensis*) and Implications for Its Conservation

Kate Burndred[1] and David Sternberg[2]

Abstract

The Cooper Creek catfish (*Neosiluroides cooperensis*) is an endangered species, endemic to the Cooper Creek catchment of the Lake Eyre Basin in Central Australia. The species is considered at risk from a range of significant biological and anthropogenic stressors, including the recent, rapid spread of translocated sleepy cod (*Oxyeleotris lineolata*) throughout its range. Little is known of *N. cooperensis* biology and ecology due to its cryptic nature and restricted distribution within a remote geographical landscape. This study undertook targeted sampling to collect critical biological information, to better evaluate the species' response to current and future threats. Despite a low catch rate, some important biological observations were made. Notably, a ripe female was collected (TL: 409 mm, W: 575.5 g) with eggs ranging in size from 2.48 mm to 3.30 mm, and an estimated fecundity of 4370 eggs. Patterns in reproductive biology indicate the species is likely to be an annual batch spawner, possibly cued by early summer storms. Dietary analysis showed a narrow diet [Levins' standardised niche breadth: 0.33 (B_A)] dominated by gastropods and bivalves. Findings from this study provide significant new information regarding the species' reproductive biology and ecology, in particular life-history similarities and dietary overlap with invasive *O. lineolata*. Our findings validate some of the perceived threats to *N. cooperensis* and will enable future work to accurately assess risks to population viability. Ultimately, these findings will be integral to the development of a conservation plan for Cooper Creek catfish.

Keywords: Lake Eyre Basin, Plotosidae, endemic species, sleepy cod (*Oxyeleotris lineolata*), life history

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Burndred, K., & Sternberg, D. (2022). Biology and reproductive ecology of the endangered Cooper Creek catfish (*Neosiluroides cooperensis*) and implications for its conservation. *Proceedings of The Royal Society of Queensland*, *131*, 3–13. https://doi.org/10.53060/prsq.2022-02

Introduction

Neosiluroides cooperensis (Allen & Feinberg, 1998) is endemic to the Cooper Creek system in the Lake Eyre Basin drainage in Central Australia. This monotypic genus belongs to the Plotosidae family and shares an ancient lineage with other catfish species found across the Basin [i.e. *Neosilurus hyrtlii* Steindachner, 1867; *Neosilurus gloveri* Allen & Feinberg, 1998; and *Porochilus argenteus* (Zeitz, 1896)]; however, it remains the sole member of the *Neosiluroides* genus (Wager & Unmack, 2000). The species has important ecological value and cultural significance to local Indigenous groups, the Dieri and the Yandruwandha Yawarrawarrka,

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who traditionally identify *N. cooperensis* as 'Capi' – a customary food source still sought after today (Constable et al., 2015).

Historically, *N. cooperensis* may have been found throughout the wider Lake Eyre Basin waterway network during the wetter climatic phases of the Pleistocene era (Unmack, 2001); however, its present distribution is now restricted to larger, more permanent waterholes of the Cooper Creek system. The species has been recorded from 38 localities within the Cooper catchment, occupying an area of approximately 128 km^2 (Arthington et al., 2019). Contemporary survey data confirm this species is naturally rare across its range, typically representing less than 1% of total catch (DRDMW, 2021). The cryptic nature of *N. cooperensis* and its restricted distribution have resulted in a very limited biological and ecological knowledge base. Sparse catch records (e.g. Balcombe et al., 2007; Kerezsy et al., 2011; DRDMW, 2018) and brief biological observations from captive specimens (e.g. Unmack, 1996) are insufficient to adequately assess the risks to this species from purported threats. Key knowledge gaps remain in relation to reproductive patterns, life-history strategy, trophic status, habitat preferences and movement dynamics.

The species was listed as Endangered as part of a review by the International Union for Conservation of Nature (IUCN) in 2019, due to significant conservation threats (Arthington et al., 2019). The recent introduction of the invasive sleepy cod [*Oxyeleotris lineolata* (Steindachner, 1867)], which has colonised most of the Cooper catchment within a decade of introduction, represents the greatest potential threat to *N. cooperensis* through both predation and competition (Sternberg & Cockayne, 2018). Furthermore, under a conservative climate scenario, waterhole persistence is predicted to decrease over time (Cockayne, 2021), which will reduce available habitat for *N. cooperensis* and likely compound competition with *O. lineolata* (Morrongiello et al., 2011; Arthington et al., 2019).

This paper aims to fill key biological and ecological knowledge gaps for *N. cooperensis* using data obtained from wild specimens. Findings from this study of wild specimens will supplement the recent review of threats to *N. cooperensis* and its listing as Endangered on the IUCN Red List of Threatened Species (Arthington et al., 2019), and this paper will discuss findings in the context of the species' biology, ecology and interspecific relationships with translocated *O. lineolata*. Outcomes from this project will help guide future targeted monitoring activities and assist in the development of long-term recovery plans for *N. cooperensis* in the Lake Eyre Basin.

Materials and Methods

Field Collection

Specimens of *N. cooperensis* were obtained via community and citizen group fishing events, and by routine and targeted fish sampling associated with the Lake Eyre Basin Rivers Assessment (LEBRA) (Table 1). LEBRA is a monitoring program designed to assess the condition of watercourses and catchments in the Lake Eyre Basin, their related natural resources, and those factors likely to affect them such as water resource development and land use change. The main collection method for community events was daytime hook-and-line angling, while LEBRA fish sampling employs two large double-winged fyke nets (10 m wings, 12 mm mesh, 5 m funnels, 1.2 m high; T & L Netmaking, Melbourne, Victoria, Australia) and six small single-winged fykes (3 m wing, 4 mm mesh, 3 m funnel, 0.6 m high; T & L Netmaking) set overnight (<19 hrs set time) (see Sternberg and Cockayne, 2018).

Monitoring sites were selected from rivers across the Cooper Creek catchment, with an emphasis on permanent waterholes representative of the surrounding landscape, hydrology, water chemistry and geomorphic diversity (Thoms et al., 2009). Specimens obtained from LEBRA sampling were collected from fyke nets set near semi-submerged woody debris, at depths of less than 2 m in waterholes with previous records of *N. cooperensis*. Specimens obtained from community events were all angled from within the main channel and littoral zones of waterholes. Stream flow and rainfall records representative of conditions preceding 2019–2020 sampling periods are provided in Figure 1. During the weeks preceding the targeted sampling in November 2019, late spring and early summer storms were occurring across the district – producing small, scattered rainfall events (<10 mm mean hourly total).

Table 1. Location and number of *N. cooperensis* collected between 2019 and 2020 (LEBRA: Lake Eyre Basin Rivers Assessment). All specimens were frozen on site for later analysis, except LEBRA targeted samplings which were processed *in situ* and subsequently frozen.

Activity	Location	Sampling dates	Collection method	Number captured
Community events				
Windorah Yellowbelly Fishing Competition	Cooper Creek at Windorah Bridge (vicinity) (25.3701°S, 142.7429°E)	May 2019	Angling	0
Longreach Sleepy Claw Bust	Thomson River at Apex Park (vicinity) (23.4084°S, 144.2298°E)	May 2019	Angling	0
Isisford Fishing Competition	Barcoo River at Oma Waterhole (24.2875°S, 144.3125°E)	July 2019	Angling	0
Longreach Yellowbelly Fishing Classic	Thomson River at Apex Park (vicinity) (23.4084°S, 144.2298°E)	August 2019	Angling	7
LEBRA targeted sampling	Thomson River at Stonehenge (24.4481°S, 143.3543°E)	November–December 2019	Fyke and seine nets	0
	Thomson River at Longreach weir (23.3645°S, 144.2945°E)			1
	Thomson River at Apex Park (vicinity) (23.4084°S, 144.2298°E)			0
	Thomson River at Camoola (22.9884°S, 144.5078°E)			0
LEBRA annual monitoring	Thomson River at Ag College waterhole (23.3512°S, 144.3292°E)	May–June 2019; August–September 2020	Fyke and seine nets	0
	Towerhill Creek at Lamermoor (21.3431°S, 144.6475°E)			0
	Cornish Creek at Bucksleas (22.4701°S, 144.8745°E)			0
	Barcoo River at Avington Road (24.3078°S, 145.2889°E)			0
	Barcoo River at Killman Waterhole (24.2758°S, 144.3661°E)			0
	Barcoo River at Retreat (25.1855°S, 143.2814°E)			0
	Kyabra Creek at One Mile (25.8482°S, 143.0517°E)			0
	Vergemont Creek at Noonbah (24.0844°S, 143.1285°E)			0
	Darr River at Darr (23.216°S, 144.0817°E)			0
	Thomson River at Stonehenge (24.4481°S, 143.3543°E)			0
	Cooper Creek at Windorah Bridge (25.3701°S, 142.7429°E)			1
	Wilson River at Noccundra (27.8244°S, 142.5873°E)			0
	Cooper Creek at Durham Downs (27.0524°S, 141.9037°E)			1

A post-winter flow event occurred in the upper and mid reaches of Cooper Creek in early November and lasted for approximately two weeks, before the channels returned to zero flow.

All *N. cooperensis* specimens were euthanised in an ice slurry at the point of capture and transferred frozen to the laboratory for entire processing, except for specimens collected during targeted monitoring which were processed immediately to assess reproductive stage and then frozen for later analysis. All non-target fish species were removed from nets upon collection and returned to the water immediately.

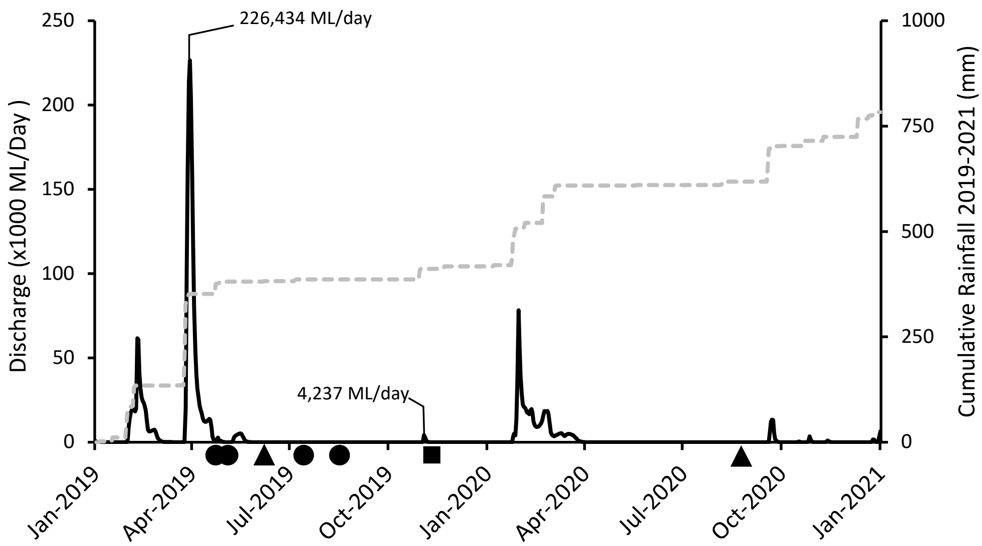

FIGURE 1. Discharge (ML/day: black line) and rainfall (mm/day: grey dashed line) representative of conditions recorded in Cooper Creek throughout sampling activities (GS 003203A; Thomson River at Stonehenge). Symbols below axis: Circle = Community sampling events; Square = LEBRA targeted sampling; Triangle = LEBRA annual monitoring. See Table 1 for details of sampling locations.

Laboratory Processing

Once in the laboratory, frozen fish samples were defrosted and excess water removed. The sex of fish was determined by examining the urinogenital papilla (Unmack, 1996). Morphometric characters were measured to the nearest millimetre using vernier callipers, according to Pusey et al. (2004). Wet weight was determined to the nearest 0.01 g. A length–weight relationship was obtained by applying the exponential regression equation: $W = a(SL)^b$, where W = Weight (g), SL = Standard Length (mm), a = the intercept and b = the slope of the log-transformed linear regression (Sternberg & Cockayne, 2015).

To remove the gonads, an incision was made from the urinogenital pore through the pelvic girdle towards the head, exposing the abdominal cavity. Gonads were then dissected, weighed, and staged according to Pusey et al. (2004). Mature gonads were inspected, and where possible, egg diameter was measured to the nearest 0.1 mm and egg weight was determined to the nearest 0.01 g. The morphology of eggs was closely inspected under a compound microscope (ZEISS Axiolab5, Carl Zeiss Pty Ltd, Germany) and described in detail. Gonadosomatic index (GSI) is a metric that represents the gonad mass as a proportion of the total body mass and was calculated as: GSI = (Weight[gonad] ÷ Weight[wet]) × 100 for mature males and females (see Pusey et al., 2004). An increased GSI value indicates further development of the gonads. GSI of eviscerated individuals was also calculated using the formula: GSI[eviscerated] = (Weight[gonad] ÷ Weight[eviscerated]) × 100 for ripe males and females. Summary statistics (mean, standard error and range) were generated for all reproductive traits for Stage I, II, III, IV and V males and females. Fecundity was estimated using the gravimetric method: after determining the weight of the ovary, three small samples of 0.1 g each were taken from the anterior, middle and posterior of the ovary. The number of ova in each sample was counted, and total number of ova calculated using the formula: Fecundity = (average number ova from sample) × (total ovary weight) ÷ 0.1.

Stomach contents were removed by dissecting the digestive tract between the œsophagus and the intestine, and eviscerating prey items into a bag. Contents were then weighed and pressed to an even thickness of 2 mm, visually scored over graded graph paper with the relative volumetric contribution of prey items to the total gut content measured in the number of graph squares covered (Hyslop, 1980; Balcombe et al., 2005). Prey categories were derived from Pusey et al. (2004) and included fishes, macrocrustaceans, microcrustaceans, other aquatic invertebrates, terrestrial invertebrates, terrestrial vertebrates, plants, algae, detritus, and unidentified. Allotted squares were summed for each diet category and expressed as the percentage of total dietary contribution. Unidentified food items were omitted from all diet analyses. Eviscerated fish weight was calculated as: Weight[eviscerated] = Weight[wet] – (Weight[gonad] + Weight[prey]), which includes the stomach tissue but not the stomach contents (i.e. prey items).

Results

Sample Size

Ten specimens (3 males, 7 females) were sampled from four sites across three sampling events (June 2019, August 2019, November 2019). Total length ranged from 196 mm to 409 mm (mean 328.5 mm), and weight ranged from 51.5 g to 575.50 g (mean 319.15 g). The standard length–weight relationship was derived from the log-transformed linear regression: W = 3.3473(SL) – 5.8828, and best described as: $W = 1\times10^{-5.8828}(SL)^{3.3473}$, $R^2 = 0.97$, $P < 0.001$, $n = 10$.

Reproductive Biology

Sexual dimorphism was restricted to differences in urinogenital papilla shape: females having a smooth, rounded triangular shape; males having a longer, tapered, cylindrical shape.

Two *N. cooperensis* collected in June 2019 were both relatively small males (L_T = 196 mm, W_W = 51.5 g and L_T = 302 mm, W_W = 142.5 g) in immature (GSI_E = 0.20%) and early-developing (GSI_E = 0.14%) stages, respectively. One immature male (L_T = 223 mm, W_W = 78 g, GSI_E = 0.13%) and six females ranging from early to late developing stage (GSI_E = 0.56%–3.41%) were collected in August 2019 (Table 2). For females where developing ova were measurable, the standard length–fecundity relationship was derived from the log-transformed linear regression: F = 5.638(SL) – 10.771, and best described as: $F = 1\times10^{-10.7707}(SL)^{5.6368}$, $R^2 = 0.73$, $P < 0.05$, $n = 6$.

The tenth specimen collected in November 2019 was a gravid female (L_T = 409 mm, W_W = 575.5 g, GSI_E = 8.91%) (Figure 2; Table 2). No eggs were exuded from the gravid specimen when firm pressure was applied, and no eggs were present in the oviduct upon dissection. The paired ovaries were turgid, well vascularised, approximately equal in size, weight and shape, and uniform in texture. *In situ* ova were evenly distributed from the posterior to the anterior of the ovary, and their size and shape were relatively consistent; little atresia was observed (<1.0 %). The eggs were spherical, translucent, bright amber in colour, and slightly adhesive with no oil droplets or observable surface structures. Mature eggs ranged in diameter from 2.48 mm to 3.30 mm (mean egg diameter = 2.96 mm), and weight from 0.0129 g to 0.0164 g (mean egg weight = 0.0147 g). Total fecundity was estimated to be 4370 eggs.

FIGURE 2. Peritoneal cavity of Stage V, gravid female *N. cooperensis* (LT = 409 mm) showing posterior urinogenital papilla (left of image), paired ovaries with vascular network (centre), and visceral organs with mesentery containing larval parasitic nematode (unknown species) (right). Scale in millimetres.

Table 2. Reproductive parameters derived from female *N. cooperensis* specimens (n = 7). Data presented are minimum–maximum (mean ± standard error). Total length (L_T); wet weight (W_W); eviscerated gonadosomatic index (GSI_E); maturity stages follow Pusey et al. (2004).

Parameter	Stage I	Stage II	Stage III	Stage IV	Stage V
Count (n)	1	2	2	1	1
L_T (mm)	371	336–358 (347 ± 11)	378–391 (384.5 ± 6.5)	321	409
W_W (g)	461	297–376 (337 ± 39)	453–483.5 (468.3 ± 15.25)	273	575.5
GSI_E (%)	0.563	0.80–0.96 (0.88 ± 0.08)	1.73–2.04 (1.89 ± 1.56)	3.41	8.91
Egg weight (g)	—	(0.0008 ± 0.00005)	(0.0011 ± 0.0001)	(0.0072 ± 0.0005)	(0.0145 ± 0.0004)
Egg diameter (mm)	<0.1–0.8	0.4–1.4 (0.87 ± 0.05)	0.6–1.5 (1.10 ± 0.06)	1.8–2.6 (2.36 ± 0.09)	2.48–3.30 (2.96 ± 0.09)
Total fecundity	—	1826–3972 (2899 ± 1073)	4013–6177 (5094 ± 1082)	1235	4370

Targeted sampling between November and December 2019 found individuals of the catfishes *N. hyrtlii* and *P. argenteus* to be gravid and running ripe, gauged by distended bellies with some exuding spat and spawn when slight pressure was applied. This was confirmed by dissecting a sample of individuals. Some specimens of *O. lineolata* were also observed to be gravid, running ripe and spent; also gauged by the swollen appearance of bellies and confirmed by dissecting a sample of individuals.

Dietary Analysis

All *N. cooperensis* specimens had dietary matter in their stomachs, and fullness ranged from 10% to 70% (Table 3). Gut fullness was not influenced by fish size (W_W: F = 1.55, p >0.05, R^2 = 0.163; L_T: F = 1.78, p >0.05, R^2 = 0.161). Levins' standardised niche breadth was low (B_A = 0.33). *Neosiluroides cooperensis* diet was dominated by molluscs (*Velesunio* spp., *Notopala* spp.) and macrocrustaceans (*Macrobrachium australiense*) in most individuals (Table 3). No evidence of piscivory or consumption of terrestrial food sources was observed.

Morphology

All *N. cooperensis* specimens were in excellent condition, with no external signs of disease or injury at time of capture. Upon dissection, the eggs and larvae of parasitic nematodes (unknown species) were observed throughout the mesentery of the abdominal cavity of eight specimens (Figure 2).

Table 3. Diet breadth and composition of 10 wild-caught *N. cooperensis* from the Cooper Creek catchment. Data are minimum–maximum (mean ± standard error).

Parameter (unit)	
Count (n)	10
Total length (mm)	196–409 (328.5 ± 21.2)
Weight (g)	51.50–575.50 (319.15 ± 54.5)
Gut fullness (%)	10–70 (34 ± 6.4)
Gut weight (g)	1.90–18.30 (9.10 ± 1.7)
Diet category (% contribution)	
Molluscs	0–80 (30 ± 9.4)
Macrocrustaceans	0–80 (25 ± 8.9)
Microcrustaceans	0–10 (1 ± 0.9)
Other aquatic invertebrates	0–10 (1 ± 0.9)
Vegetation	0–20 (7 ± 1.7)
Algae	0–5 (1 ± 0.5)
Detritus	0–15 (5 ± 1.6)
Unidentified	0–100 (30 ± 9.8)
Levins' standardised niche breadth (B_A)	0.33

Observation of the buccal cavity showed two discrete patches of villiform maxillary teeth under the fleshy upper lip, and a circular vomerine tooth patch consisting of clustered smooth molariform teeth (Figure 3 and Figure 4). The lower jaw contained a narrow band of villiform mandibular teeth behind the inferior lip, leading into a wider patch of irregularly arranged smooth molariform teeth. Two large, elliptical patches of coarse pharyngeal teeth border the œsophageal opening.

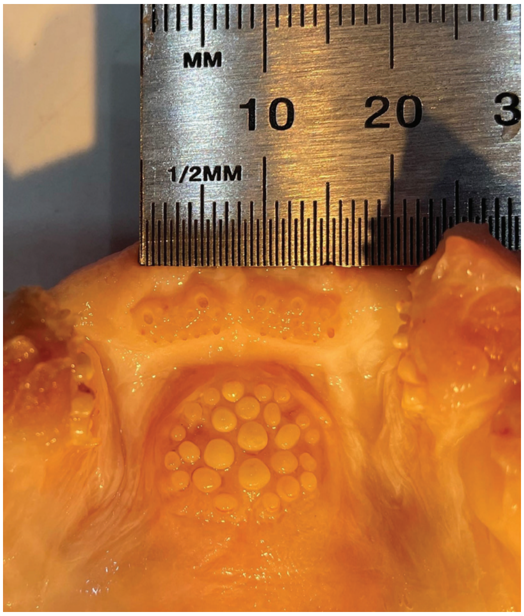

FIGURE 3. Dissected upper jaw of adult *N. cooperensis*, demonstrating the arrangement of the maxillary and vomerine tooth patches.

FIGURE 4. Dissected upper jaw of adult *N. cooperensis*, showing sharp villiform teeth which sit under the fleshy upper lip.

Discussion

This study has provided the first confirmed evidence of a wild, gravid female *N. cooperensis* and offers novel biological and life-history information relating to the trophic and reproductive ecology of this species. Considering the recent declaration by the IUCN that *N. cooperensis* is Endangered, this information is valuable for quantifying the potential interspecific threats from *O. lineolata* in the Lake Eyre Basin.

The detailed observations from a ripe specimen help augment some of the existing hypotheses regarding the species' spawning strategies and question current theories pertaining to their breeding biology. The eggs from the wild specimen were smaller than reported for a captive specimen of similar size: 2.48 mm to 3.30 mm (mean = 2.96 mm), c.f. 2.75 mm–4 mm (Unmack, 1996); and not significantly larger than the eggs of other Australian plotosids (Pusey et al., 2004; Wager & Unmack, 2000). The eggs were strongly demersal, lacking oil constituents, and although they were slightly adhesive, possessed no adhesive structures suggesting they are adapted to settle onto substrate. The uniform distribution of mature eggs throughout the ovary indicates that *N. cooperensis* is indeed likely to spawn annually (Kereszy, 2010), in one episode or in successive batches over a short time frame (i.e. days to weeks).

The theory that *N. cooperensis* spawns in summer, at water temperatures around 26°C (Unmack, 1996), is supported by previous observations of female *N. cooperensis* with distended bellies consistent with egg production, recorded during early summer (Kerezsy, 2010; DRDMW, unpublished data). Furthermore, a single male displaying a swollen, highly vascularised urinogenital papilla has been recorded in November (DRDMW, unpublished data). During targeted sampling, abundant, medium-bodied, non-target species were observed ripe and running ripe (*P. argenteus*, *N. hyrtlii* and *O. linoleata*), suggesting local conditions had triggered gonad development and fish were preparing to spawn. Sampling was undertaken in the weeks following several small rainfall events; water levels were slowly receding, daily mean water temperatures ranged from 27.3°C to 34.0°C, and occasional storms were occurring throughout the Cooper catchment daily. Preparation for a synchronous spawning event associated with these 'optimal' conditions would ensure maximum exploitation of invertebrate resources following within-channel flow pulses, and greater chances of juvenile recruitment (Humphries et al., 1999; King, 2004). It therefore seems most likely that *N. cooperensis* spawns on an annual cycle in the warmer summer months, adapted to take advantage of early or intermittent summer flows that drive increased productivity within waterholes (Welcomme et al., 2006; Kerezsy, 2010; Kerezsy et al., 2011). Unmack (1996) observed that in comparison to other Australian plotosids, Cooper Creek catfish have a much lower fecundity with significantly larger eggs and may be capable of mouthbrooding. The present study recorded smaller egg size and higher fecundity in a mature wild-caught female; therefore, it seems that mouthbrooding is less plausible. The theory should not be discredited, though, until ripe and/or spent male specimens are closely inspected.

In comparison to other plotosids, the morphology of *N. cooperensis* eggs and ovaries is remarkably similar to *Tandanus tandanus* (Mitchell, 1838), which are nest-building, annual batch spawners that provide a high level of parental care (Burndred et al., 2017). Relatively stable flow conditions are required during the early development phase of *T. tandanus* larvae, when males closely guard and protect their brood, a strategy that seems unlikely to apply to *N. cooperensis* due to their opportunistic spawning associated with unpredictable hydrology. In contrast, the co-occurring *N. hyrtlii* is a widely recognised annual flood spawner (e.g. Kerezsy et al., 2011), broadcasting a comparatively high number of smaller, strongly demersal eggs, which develop in substrate without parental care (Orr & Milward, 1984). The way in which male and female *N. cooperensis* coalesce in highly turbid conditions, the mechanisms of spawning and fertilisation, the duration of egg and larval development, and the mode of parental care (if any) remain largely unknown.

Dietary analysis confirms that *N. cooperensis* is an invertivore favouring mussels, macroinvertebrates and snails (Unmack, 1996; Wager & Unmack, 2000). The positioning of the underslung mouth, lined with bands of villiform teeth, is well suited for striking benthic prey, and the form and arrangement of vomerine teeth in the upper buccal cavity are adapted for crushing hard shell and chitin. Importantly, the dietary habits of *N. cooperensis* reveal a relatively high trophic niche overlap with *O. lineolata*. Both species show a dietary preference for macrocrustaceans and other aquatic invertebrates (Pusey et al., 2004); however, in the Lake Eyre Basin, fishes also dominate the diet of *O. lineolata* (Sternberg & Cockayne, 2018). This translocated species was also found to prey on juvenile and small plotosid catfish (*P. argenteus*) (Sternberg & Cockayne, 2018), suggesting that *N. cooperensis* is likely to be impacted by *O. lineolata* through both competition for food and direct predation. These interactions are predicted to intensify during dry periods, when waterholes become isolated and contract to a series of pool habitats. In the Lake Eyre Basin, waterhole persistence is predicted to reduce as much as 30% by 2070 based on current global warming trends (Cockayne, 2021), suggesting the two species will most likely incur increased interactions as available dry season habitat declines throughout the Cooper Creek catchment. Furthermore, the strength of this interspecific competition is likely to become more intense due to shifting population structures and changing reliability of shared food resources, as seen in other catchments (Olden et al., 2008; Morrongiello et al., 2011). Fish assemblage shifts caused by the incursion and integration of *O. lineolata* have been postulated by Kerezsy et al. (2014) and Sternberg & Cockayne (2018).

Although several other medium-bodied species were collected from nets during targeted monitoring, *O. lineolata* dominated catch at all sites. This was despite high sampling effort in waterholes with relatively consistent *N. cooperensis* catch rates, at a time when the species was most likely to be active (DRDMW, unpublished data). It is accepted that *O. lineolata* has colonised most of the Cooper catchment over the last decade (Sternberg & Cockayne, 2018), and although the unexpectedly low *N. cooperensis* abundance recorded in this study may simply be due to chance, it may represent a tangible shift in fish population structure, particularly in major waterholes.

The presence of mature, running ripe and spent *O. lineolata* in all targeted waterholes is of notable concern. This study provides further evidence of niche overlap with *N. cooperensis*, where mature adults may be competing for habitat, specifically during spawning, and developing larvae and juveniles may compete for resources following flood events. *Oxyeleotris lineolata* are highly fecund serial spawners (Herbert & Graham, 2004), which are likely to spawn over a prolonged period in the Cooper Creek catchment, particularly when storms are prevalent. Larvae develop rapidly and are capable of exogenous feeding at hatching (Herbert & Graham, 2004), so the likelihood of larval and juvenile *O. lineolata* overlapping with larval and juvenile *N. cooperensis* is very high. Interspecific competition that persists across multiple life stages is likely to place substantial pressure on native fish species, particularly in times of prolonged drought and environmental stress when resources are limited. Furthermore, it is unclear to what extent other factors such as meso- and microhabitat segregation may influence the strength of interspecific niche overlap throughout the species' life stages. Further detailed research into the early life history of *N. cooperensis* will help to identify critical requirements for their successful recruitment, and therefore enable measurement of the intensity and impacts of competition with young-of-year *O. lineolata*.

Identifying the factors that give introduced species competitive advantages or disadvantages over native species is a key requirement for determining and managing the threat of alien fish species, particularly under future climatic scenarios. Given their predominantly benthic habitat, and confirmed dietary and reproductive overlaps, *O. lineolata* and *N. cooperensis* are highly likely to interact frequently, particularly during times of waterhole drying. Under these conditions, *O. lineolata* would be expected to maintain a competitive advantage over *N. cooperensis* in the short term, due to its dietary adaptability and more aggressive nature. However, further reproductive information is required for both species to quantify the long-term population viability of *N. cooperensis* in the Lake Eyre Basin.

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Reversal of Ages of the Kalkadoon/Leichhardt Complex and the Magna Lynn Metabasalt, NW Queensland

William G. Perkins[1]

Abstract

One of the central tenets of interpretation of the Mount Isa Inlier, North West Queensland, is that there is a median underlying belt of Paleoproterozoic acid volcanics (Leichhardt Volcanics) and granites (Kalkadoon Supersuite), 1850–1860 Ma, commonly referred to as the 'Kalkadoon-Leichhardt Basement'. A primary requirement of this interpretation is that one of the main boundaries, that between the felsic Leichhardt complex and the Magna Lynn Metabasalt, is an unconformity. This boundary is everywhere serrated and complex, and the unconformity interpretation would require it to have been deformed by a system of variably plunging, refolded folds. Mapping of this boundary in the field, and using previous mapping and remotely sensed images, shows it to be better interpreted as intrusive, with isolated bodies of Magna Lynn Metabasalt within the Leichhardt complex interpreted as relict mega xenoliths, rather than fault blocks or refolded synforms. An intrusive relationship of the Kalkadoon/Leichhardt complex calls into question the relationships of the other mafic volcanic sequences across the Inlier.

Keywords: Kalkadoon Granodiorite, Leichhardt complex, Magna Lynn Metabasalt, Mount Isa Province, metasomatism

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Introduction

Background and Aim

Most current interpretations of Mount Isa Province (Queensland, Australia, Figure 1) geology are based on 1:100,000-scale mapping from the 1970s, with many now regarded as inviolate. One of these is the notion of a Paleoproterozoic 'Kalkadoon-Leichhardt Basement' (following Carter et al., 1961), overlain unconformably and conformably by sediments and a series of mafic volcanic units with a range of ages (Derrick et al., 1977; Bierlein et al., 2011; Hutton & Withnall, 2013; Gibson et al., 2018) (Figures 1, 2). This interpretation has not changed following updating of the mapping using airborne geophysical data. A key facet of this interpretation is that the Leichhardt complex is mostly an extrusive unit, consisting mainly of rhyolite (Wilson, 1983, 1987; Hutton & Withnall, 2013).

The mafic volcanics currently interpreted to be younger than the 'basement' crop out within the MYALLY, ALSACE, PROSPECTOR, MARY KATHLEEN, DUCHESS and MARRABA 1:100,000 maps (these capitals will be used throughout for the 1970s–1980s mapping). Only the relationships of the Magna Lynn Metabasalt will be addressed in this publication. Mapping by the author (Geological Survey of Queensland 2006–2010 Mount Isa Province program) and reinterpretation of that of other workers have indicated a different history from the earlier work, with significant implications for understanding the tectonic development of the Mount Isa Province.

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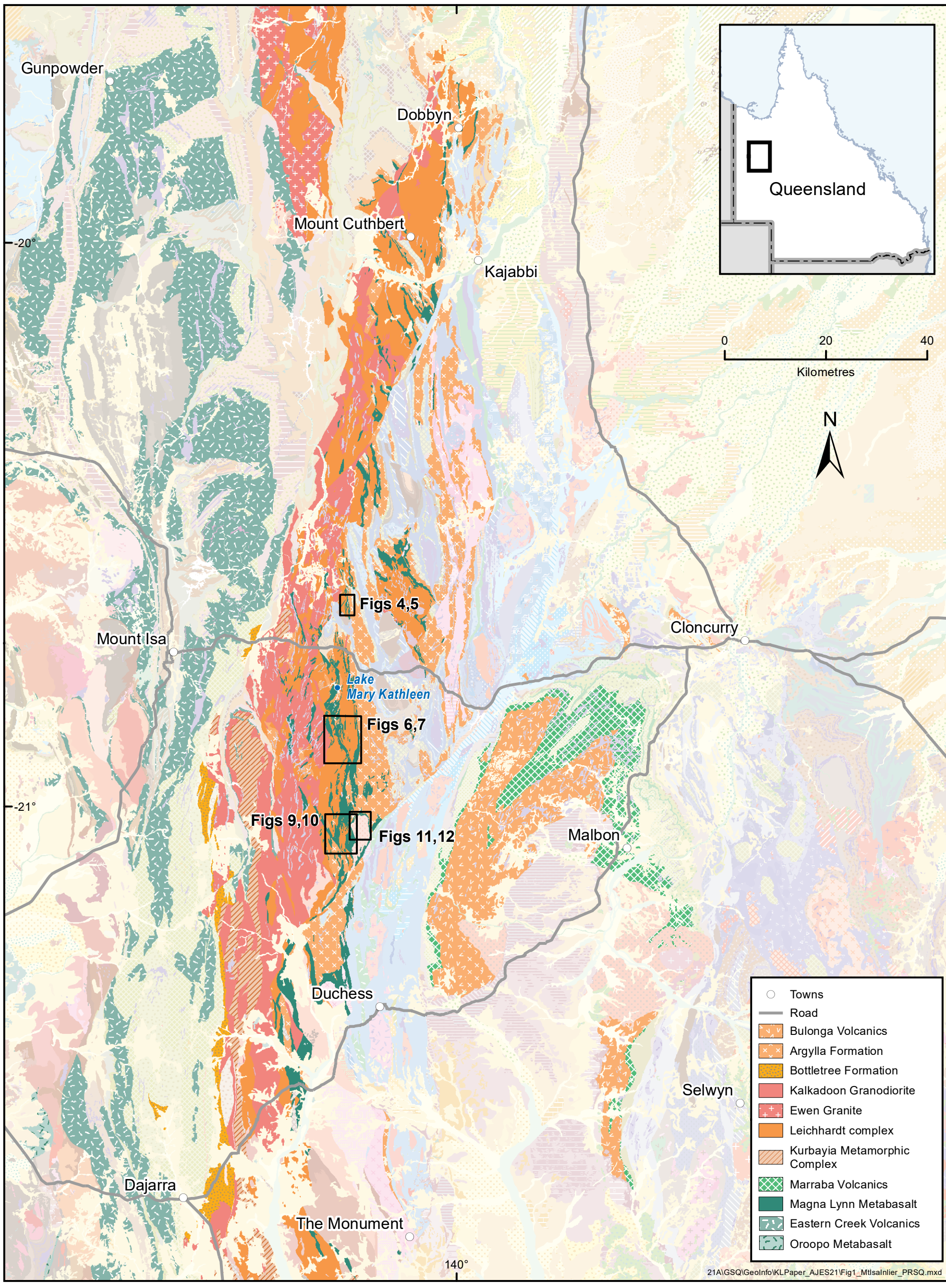

FIGURE 1. Geological unit map (modified by author) of the central portion of the Mount Isa Inlier, highlighting the Magna Lynn Metabasalt and other mafic volcanic units, together with the Kalkadoon Granodiorite, the Leichhardt complex, the Ewen Granite and the Kurbayia Metamorphic Complex. Also highlighted are the supposed felsic extrusives of the Bottletree Formation, Argylla Formation and Bulonga Volcanics. Some intrusives are interpreted within the Argylla Formation (Hutton & Withnall, 2013). The legend shows the reinterpreted age interpretation sequence of the highlighted units. Boxed areas indicate detailed maps.

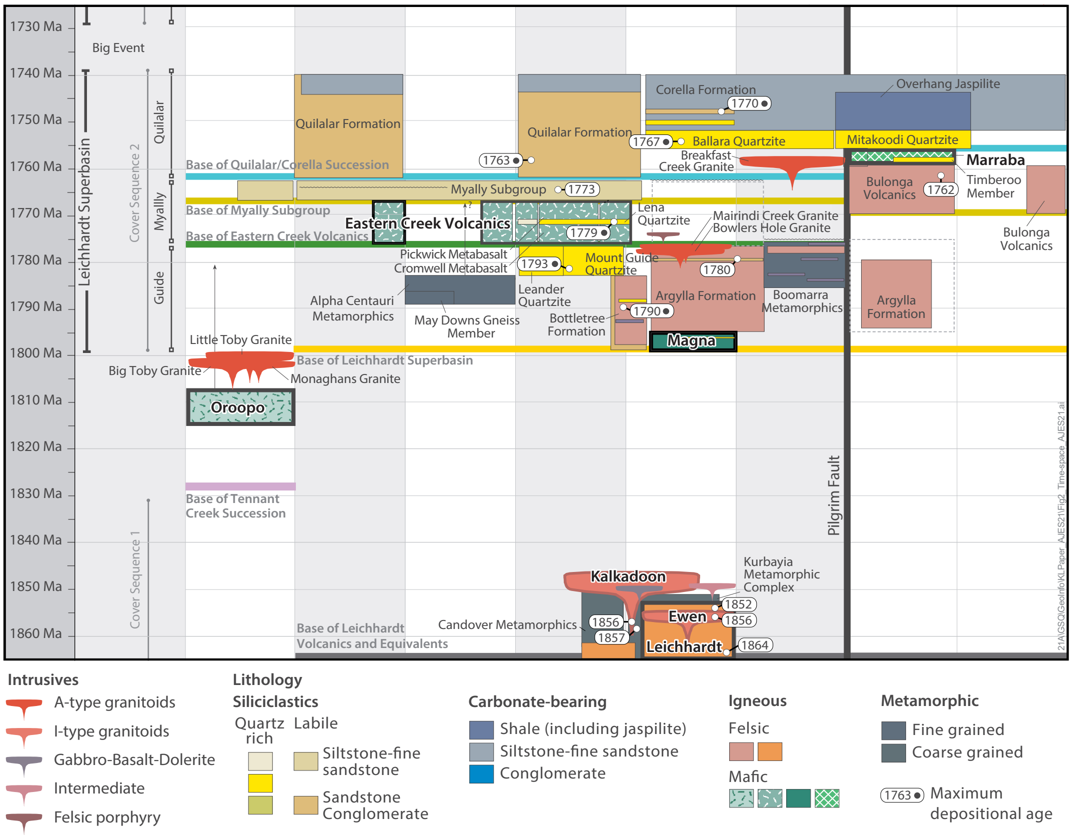

FIGURE 2. Excerpt from and simplification of a series of stratigraphic columns (Geological Survey of Queensland, 2011) across the Inlier, showing existing interpreted correlation. The mafic unit primarily addressed in this study is the Magna Lynn Metabasalt, but other mafic volcanics are also highlighted. Of significance are the four mafic units which are historically interpreted to have different ages. In addition, the Leichhardt complex, Kalkadoon Granodiorite, Ewen Granite and Kurbayia Metamorphic complex are all shown as being older than any of the mafic units. Selected isotopic dates are indicated.

Areas chosen to illustrate the revised interpretation are numbered and shown on Figure 1. The aim is to show that the Kalkadoon/Leichhardt system is intrusive into the Magna Lynn Metabasalt, rather than the universally accepted interpretation that the Leichhardt Volcanics is dominantly an extrusive unit overlain disconformably by the Magna Lynn Metabasalt. Here the intrusion is regarded as leaving residual enclaves of metabasalt with a large range of shape and size, and the term ‘Leichhardt complex’ is used in place of Leichhardt Volcanics.

Targeted geochemistry has been an important tool in discriminating between units in past work. As an example, the Leichhardt Volcanics and Argylla Formation could be separated using whole-rock geochemistry (Wilson, 1987), and the Argylla Formation is more strongly magnetic. Geochemistry has not been used in this study because it is felt that the discrimination of units was well established, and the features which are most contentious are unit boundaries. This view is not widely shared, and boundaries advanced here as being intrusive are generally regarded as unconformable. Geochronology, however, is most directly relevant to the relationships investigated here, and some targeted geochronology has been done as part of this mapping study. One dating site in the Leichhardt complex (Carson et al., 2011) was sampled in the area covered by this manuscript and is referred to below.

The Magna Lynn Metabasalt was not recognised as a separate extrusive unit by Carter et al. (1961), who regarded it as a dolerite. The unit is mostly metabasalt with some amphibolite, mafic schists and sedimentary intervals, dominantly quartzites (Hutton & Withnall, 2013). It also contains a complex system of dolerite dykes which can be traced from the felsic units on images but, in contrast with dolerites in the Eastern Creek Volcanics, are more difficult to discern in the field. Derrick et al. (1977, p. 16), who defined the formation, stated that "the Magna Lynn Metabasalt overlies metavolcanics of the Leichhardt Metamorphics (now the Leichhardt Volcanics), either conformably or disconformably". This was reaffirmed by Blake (1992). Derrick et al. (1977, p. 16) further indicated that "the upper part of the Leichhardt Metamorphics contains quartzite and acid agglomerate which passes rapidly upwards into massive metabasalt and metasediment of the Magna Lynn Metabasalt". Blake & Page (1988) claimed that the Kalkadoon Granodiorite/Leichhardt Volcanics were unconformably overlain by the Bottletree Formation, the Magna Lynn Metabasalt and the Argylla Formation.

The notion of a Kalkadoon-Leichhardt 'basement' is maintained in the most recent publications (Gibson et al., 2018; Hutton & Withnall, 2013, pp. 25, 33, 34, and a combination of their Figures 2.6 and 2.11). Figure 2 shows the existing interpretation of the relationships of rock units with four separate mafic extrusive units overlying the Kalkadoon/Leichhardt suite (from Geological Survey of Queensland, 2011). An estimate of 50 million years between that 'basement' and the overlying Magna Lynn Metabasalt is shown. Gibson et al. (2018) tentatively adopted equivalence of the Magna Lynn Metabasalt with the Eastern Creek Volcanics. An older unit relevant to the 'basement' question is the Kurbayia Metamorphic Complex (Figures 1, 2), which is locally intruded by the Kalkadoon Granodiorite, as supposedly is the 1850–1840 Ma Leichhardt complex.

In summary, the existing interpretation has a central belt of older migmatites, metamorphics, felsic volcanics and granitoids, flanked by quartzites and a series of mafic volcanics younging upwards into mostly sedimentary sequences (Gibson et al., 2018). In contrast, an alternative interpretation presented here is one of a shredded belt of Magna Lynn Metabasalt as the result of intrusion by the Kalkadoon/Leichhardt complex.

Relative Timing of Kalkadoon/Leichhardt Complex

Timing relationships of the Leichhardt complex relative to the Kalkadoon Granodiorite and Ewen Granite are equivocal. Historically, the Leichhardt complex has been interpreted as an extrusive quartz-feldspar porphyry with the Ewen and Kalkadoon suites intruding into it (e.g. Derrick et al., 1977). No field sites showing the timing relationships have been visited by the author. Age dating ranges suggest that the Leichhardt complex is older than the Kalkadoon Granite. Following Wyborn & Page (1983) and subsequent authors, ages for the units of the Kalkadoon/Leichhardt complex appear to be quite consistent and overlap within error at 1865–1852 Ma (Leichhardt complex), 1855–1864 Ma (Kalkadoon Granodiorite) and 1856–1859 Ma (Ewen Granite). The only dating on the Magna Lynn Metabasalt gives a minimum cooling age of 1521 ± 11 Ma (Li et al., 2020). Therefore, considering this unit alone, it could be older than the Kalkadoon/Leichhardt complex.

Lithology of the Relevant Felsic Units

The Leichhardt Volcanics (formerly the Leichhardt Metamorphics) consists of light- to medium-grey, variably foliated, massive to finely banded "non magnetic quartz feldspar phyric rhyolite, and subordinate metasedimentary rocks" (Hutton & Withnall, 2013, p. 32). Importantly, in the DUCHESS area the unit is described as "mainly massive rhyolitic volcanics containing quartz and feldspar phenocrysts enclosed in a very fine-grained groundmass showing primary igneous textures" (Blake et al., 1981). In the author's mapping experience, the unit does appear to be "mainly massive", and layered porphyrys are a rarity. Examples are shown of a typical outcrop of massive porphyry (Figure 3a) and a layered porphyry (Figure 3b). I. Withnall (pers. comm., 2008) has interpreted the latter as an original volcaniclastic feature. Alternatively, it could be the result of metasomatism of a sedimentary intercalation originally in the Magna Lynn Metabasalt.

In thin section at a dating locality 10 m east of a protrusion of typical massive Magna Lynn Metabasalt, "the (Leichhardt) sample is dominated by an equigranular very fine-grained groundmass of rounded to irregular quartz, biotite and minor plagioclase, with abundant large (2–5 mm) euhedral phenocrysts of plagioclase (variably replaced by secondary muscovite and sericite), quartz and sporadic K-feldspar. Flattened biotite aggregates and individual biotite flakes define a weak foliation" (Carson et al., 2008, p. 76); 21°2′32″S, 139°46′31″E. It is possible that this fits with being a 'porphyritic granite'. Hutton & Withnall (2013, p. 31) describe the Kalkadoon Granodiorite as consisting of "grey biotite (± rare hornblende) granodiorite and tonalite, pink biotite granite, minor leucogranite, muscovite granite, microgranite, porphyritic granophyre, porphyritic biotite-muscovite granite, monzonitic diorite and aplite".

FIGURE 3. (A) Typical outcrop of Leichhardt complex. Massive porphyry with light grey-brown weathering, approx. 20°43′44″S, 139°46′8″E; (B) Uncommon layered porphyry with continuous and discontinuous layers. Identified by I. Withnall, 20°54′32″S, 139°48′10″E.

Central Belt Relationships

This section addresses the relationships in the eastern part of what is generally called the Kalkadoon-Leichhardt Belt or Domain, outcropping over a strike length of 230 km and a maximum width of 28 km. It describes three separate areas from north to south, which are considered typical of the various styles of unit relationships.

The revised maps shown in Figures 4, 5, 6, 7, 9, 10 and 11, 12 are based on the existing mapping with local critical changes. Emphasis is placed on the nature of the unit boundaries, mainly between the felsic and mafic units. The combination of 3D aerial photographs and remotely sensed images, particularly from Google Earth Pro, provide exceptional contrast in texture and colour fidelity between units, and were extremely valuable in mapping. These tools were used in combination with aeromagnetics and radiometrics. The most contentious issues derive from whether the unit boundaries, particularly those between felsic and mafic units, are intrusive/metasomatic, sedimentary/unconformable or faulted.

Outcrop Pattern of the Magna Lynn Metabasalt and Nature of the Contact with the Leichhardt Complex

South of the highway (Figure 1), the Magna Lynn Metabasalt has a complex distribution pattern, with two main belts of variable widths. The western belt has two subsidiary NNW trends and coalesces with the eastern belt 16 km south of Lake Mary Kathleen. Further south, the unit again forms multiple separate bodies of variable shapes and also includes a local NNW trend. In places, such as 7 km north of Lake Mary Kathleen, the Magna Lynn Metabasalt is missing altogether, and the Kalkadoon Granodiorite is directly in contact with

Argylla Formation. Three areas have been chosen to illustrate different aspects of the Leichhardt/Magna Lynn boundary. First is a meridional belt, second a double diagonal belt, and third a northerly trending protrusion.

Meridional Contact with the Magna Lynn Metabasalt

The boundary between the Leichhardt complex and the Magna Lynn Metabasalt is everywhere ragged or sinuous, commonly having embayments extending at least 100 m into the Leichhardt complex. These features are difficult, if not impossible, to show at 1:100,000 map scale, with the result that map boundaries have been portrayed as smooth, and thus more readily seen as either stratigraphic or faulted. Many narrow 'fingers' of metabasalt project at least 1 km into the Leichhardt complex (e.g. Figures 4, 5) in what is overall a meridional boundary.

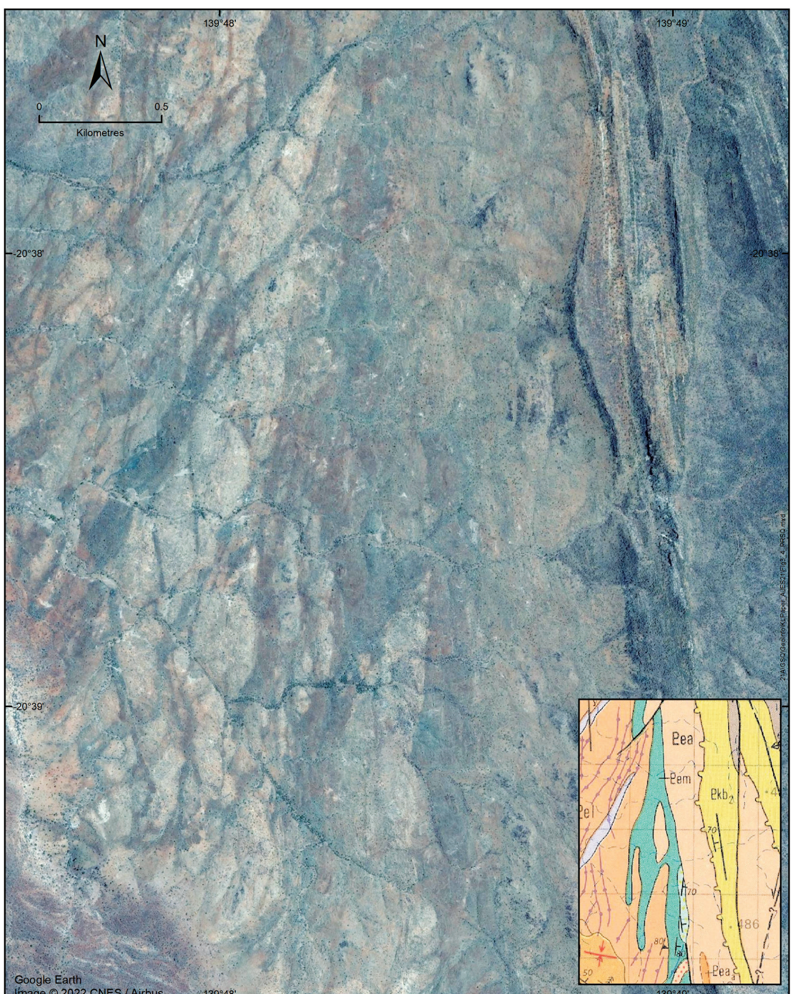

FIGURE 4. Google Earth Pro image of an area 15 km NNE of Lake Mary Kathleen, together with inset MARY KATHLEEN. The finger-like projections of the Leichhardt complex into the Magna Lynn Metabasalt are characteristic and were mostly shown in the earlier mapping. Note that the boundary between the Argylla Formation (Pea) and the Ballara Quartzite (Pkb_2) is shown as an unconformity.

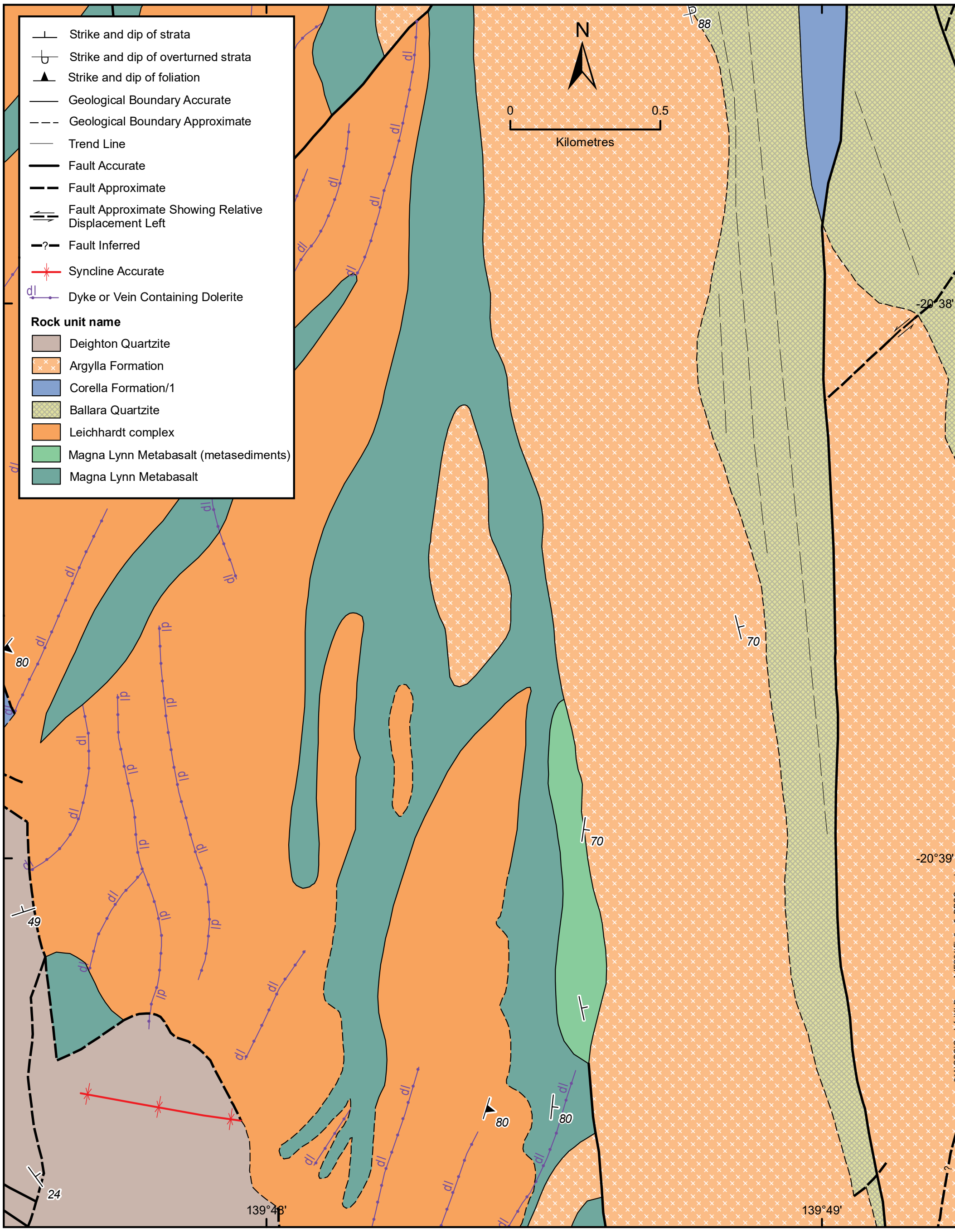

FIGURE 5. Geology of the area of Figure 4 with the Leichhardt complex interpreted as intrusive into Magna Lynn Metabasalt. It also shows Argylla Formation interpreted as intrusive into Magna Lynn Metabasalt, with the upper boundary transecting bedding in the Ballara Quartzite and also appearing to be intrusive.

Diagonal Belt of Magna Lynn Metabasalt

Located 10 km south of Mary Kathleen is a diagonal belt of Magna Lynn Metabasalt up to 1.5 km wide (Figures 6, 7). The southern boundary is deeply serrated, with embayments of the Leichhardt complex penetrating up to 500 m into the metabasalt. The northern boundary of the diagonal body is complex, with a curved inclusion of the Leichhardt complex extending 2.8 km parallel to the metabasalt boundary. The southern part of this boundary is more gently arcuate, suggesting control by a fault.

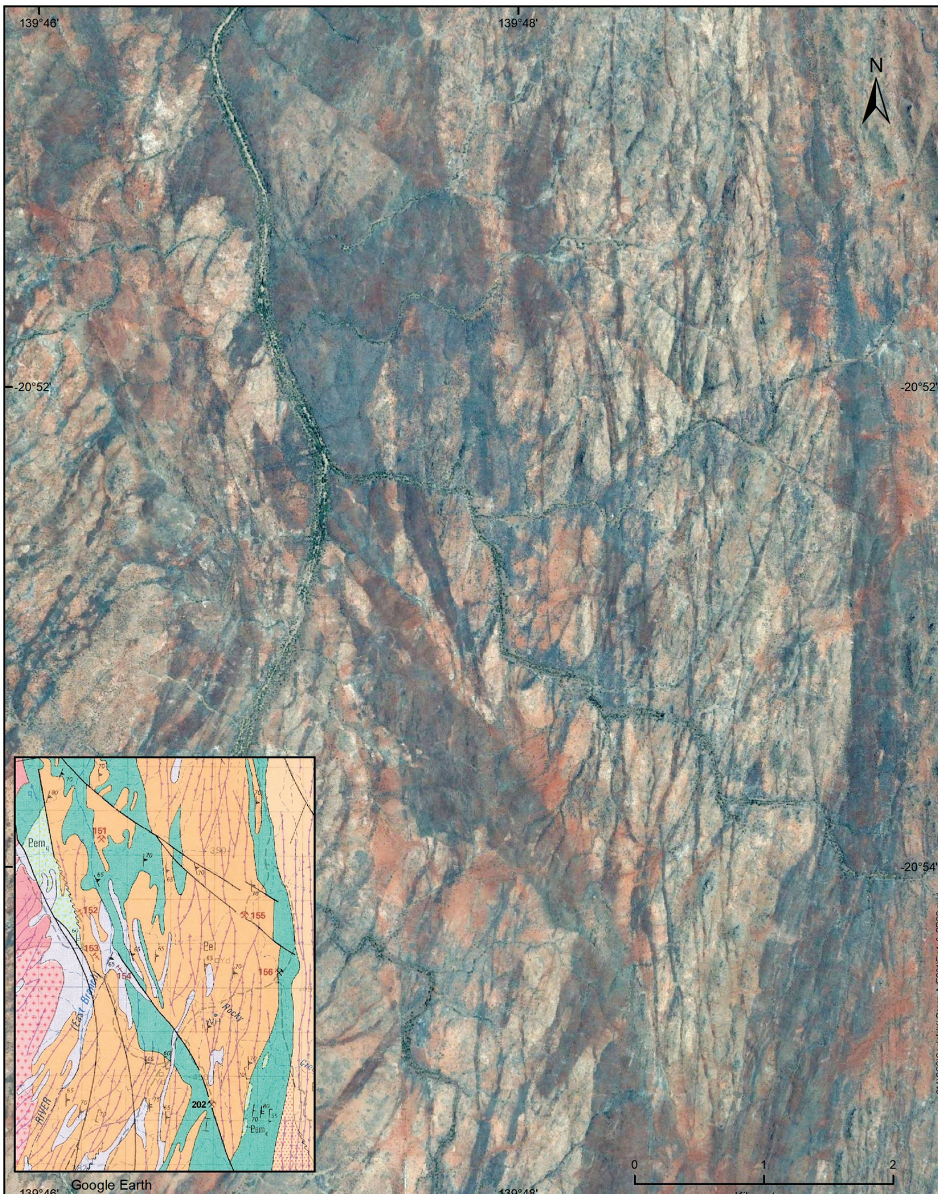

FIGURE 6. Google Earth Pro image of an area 10 km south of Lake Mary Kathleen, together with inset MARY KATHLEEN.

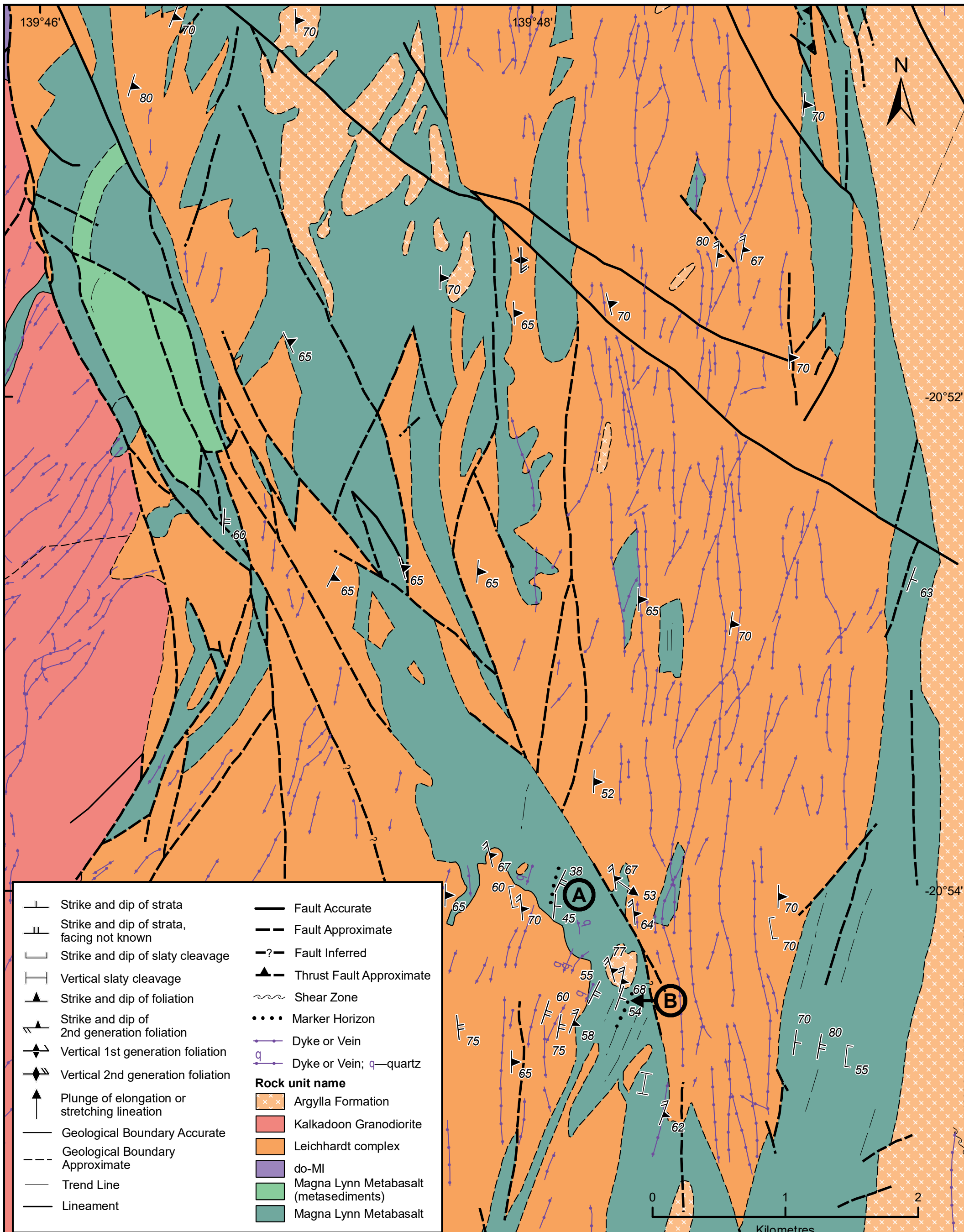

FIGURE 7. Geology of the area of Figure 6 showing a revised interpretation with the Leichhardt complex and at least part of the Argylla Formation as intrusive. The narrow quartzite unit (A) within the Magna Lynn Metabasalt is oblique to the boundary with the Leichhardt complex, indicating that the boundary is not an unconformity. The quartzite (B) is sub-parallel to (A).

Relationship of the Leichhardt Complex to Bedding in the Magna Lynn Metabasalt. At only one locality has bedding in a quartzite within Magna Lynn Metabasalt been mapped in the field adjacent to the boundary with the Leichhardt complex, although many others have been identified on images (e.g. 20°57′7″S, 139°48′4″E). In Figures 6, 7 at A, the quartzite (which is ~3 m thick) outcrops over a strike length of 160 m and terminates within 40 m of the southern Magna Lynn/Leichhardt boundary. Bedding strikes at 6° and makes an angle of 40° with the trend of that boundary. It is within 15° of the trend of a quartzite band within the metabasalt at B. Thus, the oblique boundary cannot be interpreted as a conformable or disconformable contact. Blake (1991) interpreted the boundary as a fault, which is not compatible with its highly irregular nature. In outcrop the boundary is markedly serrated with Leichhardt complex protrusions up to 170 m, and there is no evidence of a fault. Mapped and interpreted quartzite bedding trends within the Magna Lynn sequence between Lake Mary Kathleen and Figures 6, 7 are all NNE to NE, despite the complexity of the Magna Lynn/Leichhardt boundary.

Alteration within the Magna Lynn Metabasalt. On Google Earth Pro images (e.g. Figure 6), in most areas within the Magna Lynn Metabasalt there are numerous irregularly shaped, green-grey patches which appear to be transitional in character to the mappable Leichhardt complex. A possible interpretation is that these areas represent partial metasomatism of the Magna Lynn Metabasalt related to the Leichhardt complex and could agree with the “altered basic volcanics” in the unit description above. On Figure 6, within the Magna Lynn Metabasalt and up to 150 m from the southern boundary with the Leichhardt complex, is a pseudobreccia consisting of sub-rounded, dark-grey bodies in a lighter-grey matrix which has the characteristics of the Leichhardt complex. Both bodies contain feldspar laths up to 10 mm long, and the assemblage is interpreted as a partially metasomatised variant of the original metabasalt. The site is on the western margin of a slightly lighter-grey toned area on the image, which is about 100 m wide. An example of the alteration is shown in Figure 8.

FIGURE 8. Pseudobreccia consisting of irregular mafic bodies in a matrix of quartz-feldspar porphyry, Magna Lynn Metabasalt, 20°53′55″S, 139°47′59″E.

Irregular Protrusion of Leichhardt Complex Surrounded by Magna Lynn Metabasalt

Twenty-six kilometres south of Lake Mary Kathleen on DUCHESS is a 1.5 km-wide, fork-shaped protrusion of the Leichhardt complex surrounded by Magna Lynn Metabasalt (Figures 9, 10). The area is described in Bultitude et al. (1982). Dating of the Leichhardt complex in this area (21°02′32″S, 139°46′30″E) (Figure 10), gave an age of 1864 ± 3 Ma (Carson et al., 2011, p. 76). On DUCHESS inset this anomalous interpreted unconformity boundary has been rationalised with faults on the western margin. For the forked northern boundary to be an unconformity would require north-plunging triple anticlines at its extremity. Further, it requires a doubly plunging anticline at A. Smaller leucocratic bodies with the same tone as the body of the protrusion surround it (e.g. B) and were interpreted as Argylla Formation on DUCHESS inset. An alternative, given their lighter colour and lower relief, is that they are isolated intrusions of Leichhardt complex and that the entire complex is intrusive.

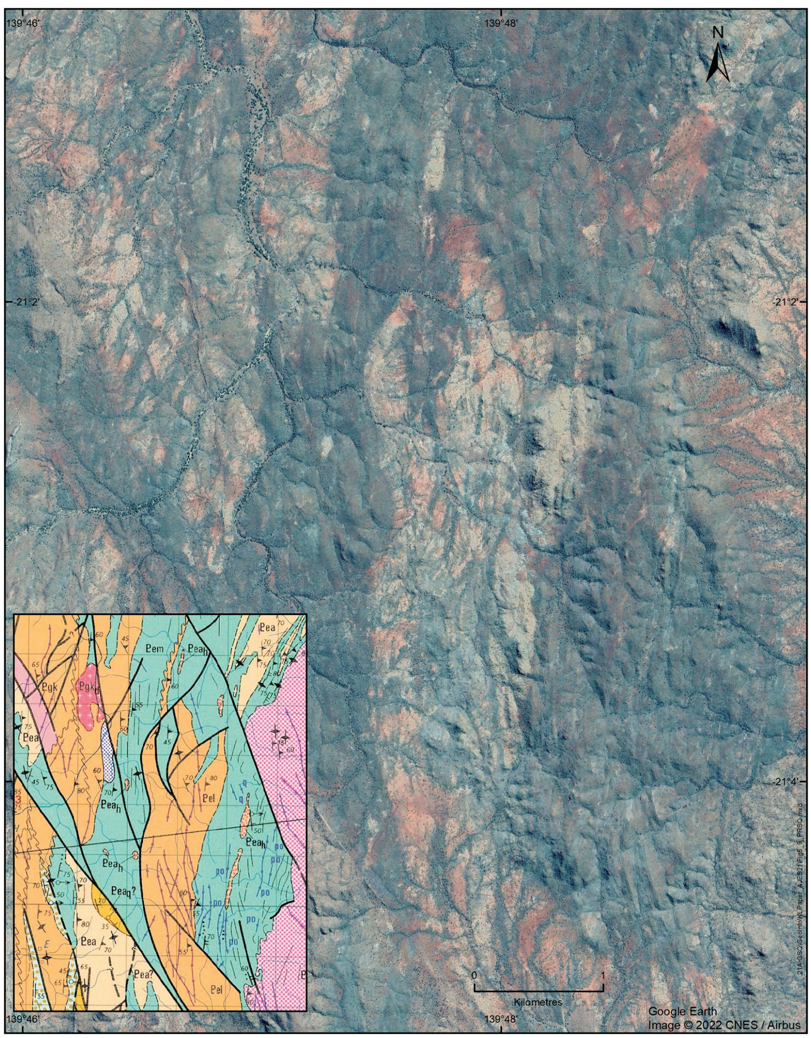

FIGURE 9. Google Earth Pro image of an irregular protrusion of the Leichhardt complex into the Magna Lynn Metabasalt. The inset from DUCHESS shows the western boundaries of the Leichhardt fingers as being mostly faulted.

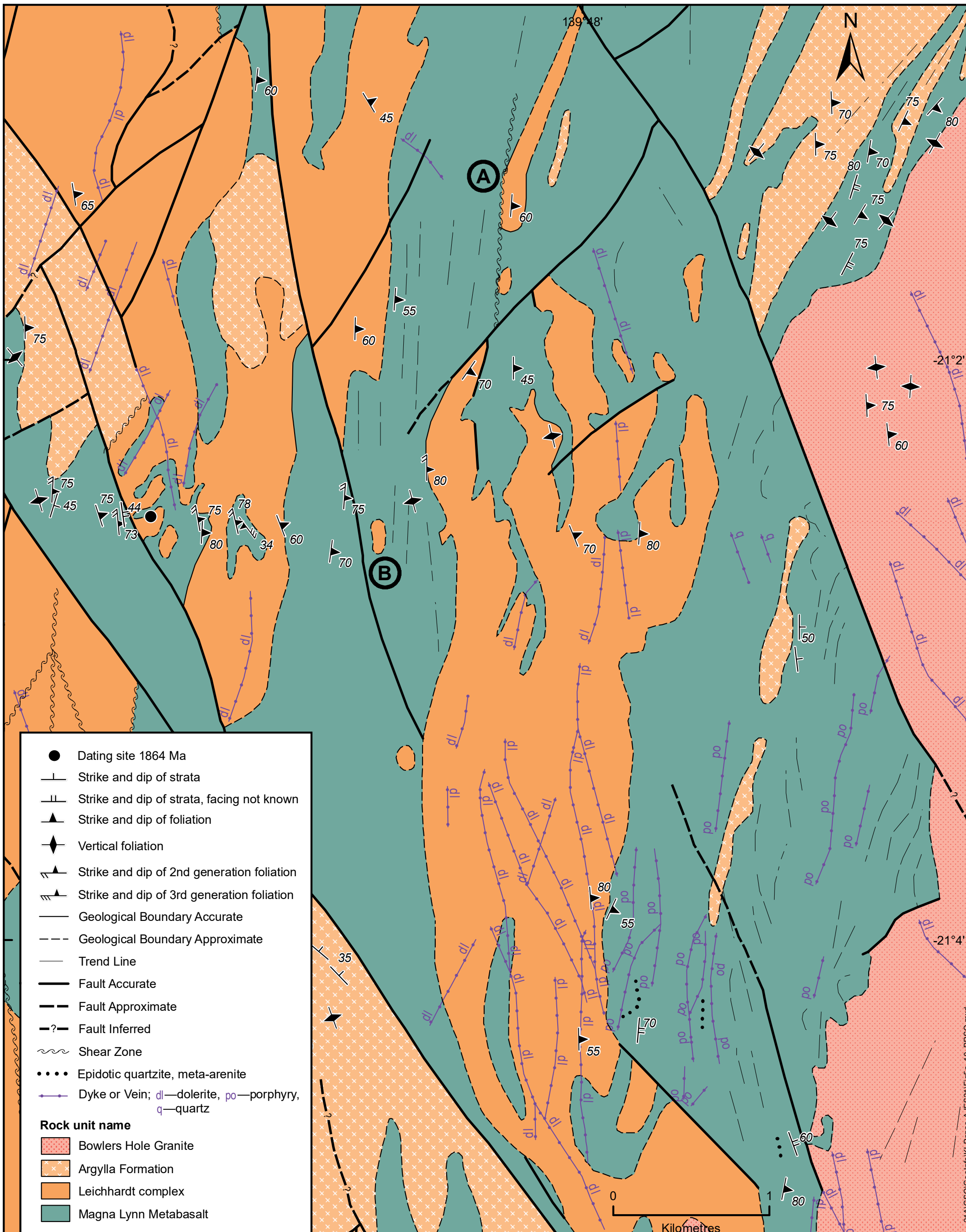

FIGURE 10. Reinterpreted area of Figure 9 showing the whole body of the Leichhardt complex as being intrusive; and smaller, lighter-coloured bodies such as B as being intrusive Leichhardt complex rather than Argylla Formation. It also shows a complex interdigitation of Leichhardt and Magna Lynn Metabasalt around the dating site.

Additional support for an intrusive interpretation for the forked Leichhardt body is the highly irregular, serrated northern boundary and 'ghosting' of metabasalt extensions within it. This margin is similar in form to the north-eastern boundary between the Bowlers Hole Granite and the Magna Lynn Metabasalt 4.5 km to the ENE (Figures 11, 12). Here, the granite is accepted as intrusive, with the same age as the Argylla Formation (1777 Ma).

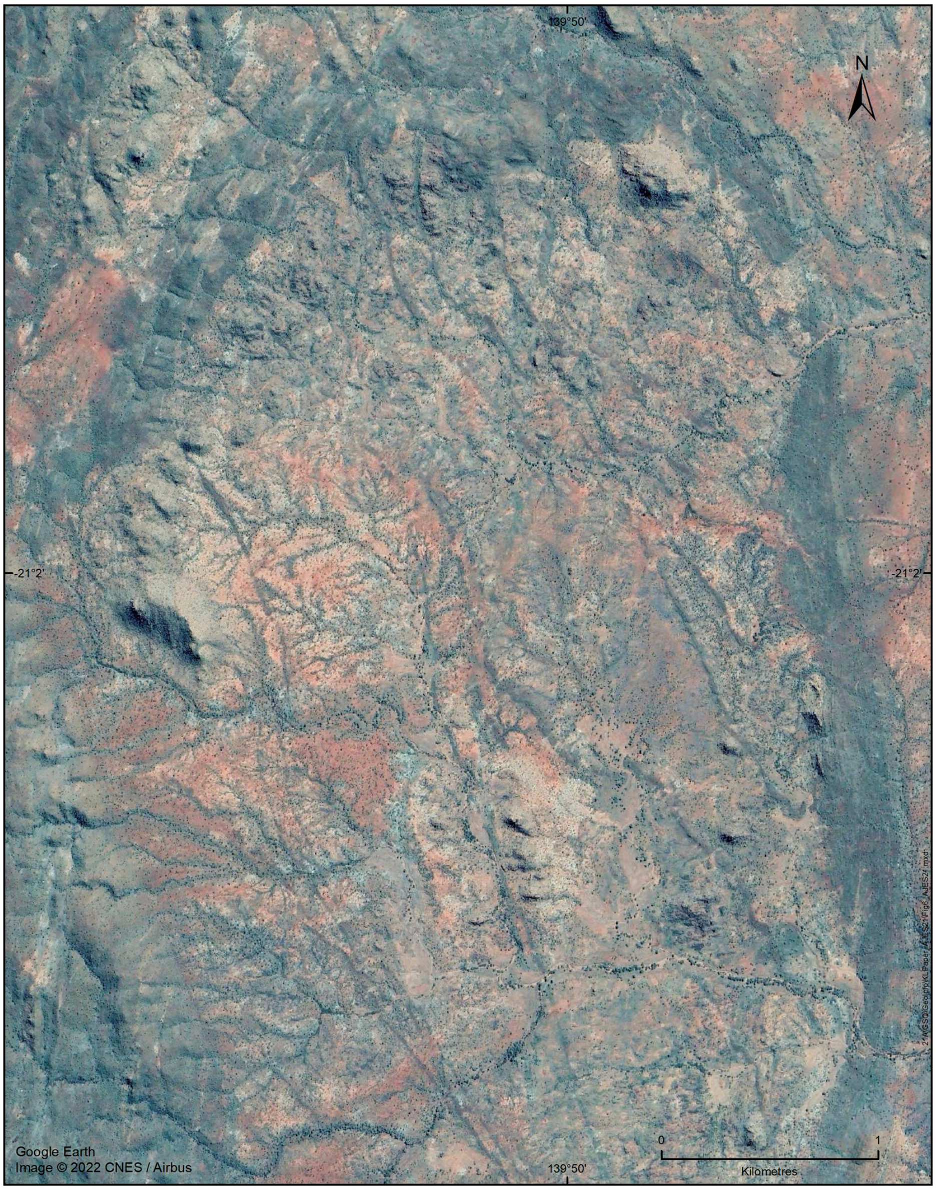

FIGURE 11. Google Earth Pro image of an area impinging on Figures 9, 10. It shows an ellipsoidal body of Bowlers Hole Granite intruding into the Magna Lynn Metabasalt. The intrusive boundary can be compared with the boundary in Figures 9, 10, which has historically always been interpreted as an unconformity.

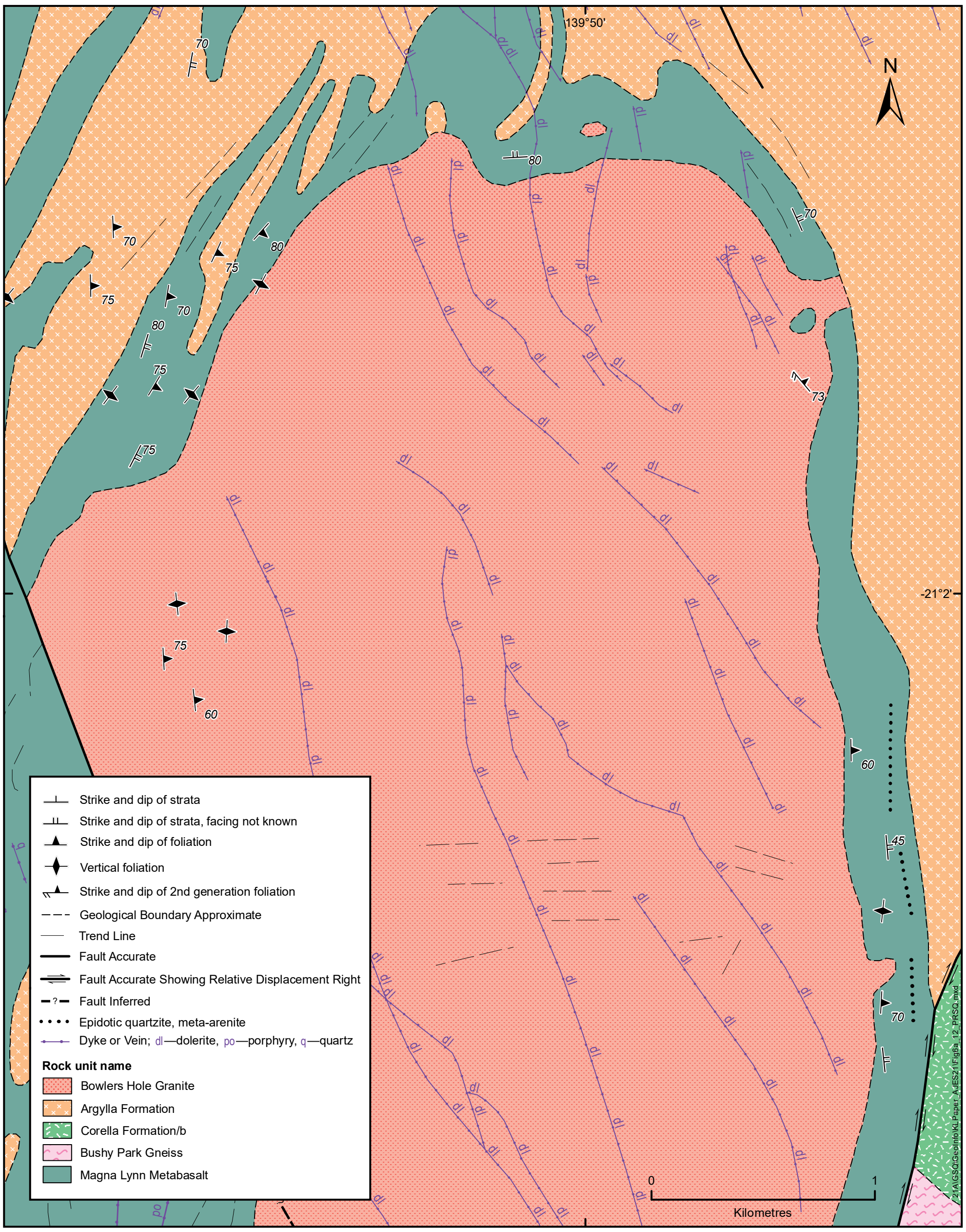

FIGURE 12. Map interpretation of Figure 11. The serrated north-eastern boundary shows similar features and metabasalt mega xenoliths to Figures 9, 10.

Characteristics of the Leichhardt/Magna Lynn Boundary

Contacts between the Magna Lynn and Leichhardt bodies may be either sharp or gradational at outcrop (Figure 13A–C) or remotely sensed scale, and where exposed, the sharp contacts have the same serrated boundaries as those bordering metabasalt xenoliths within the body of the quartz-feldspar porphyry. This suggests that the boundaries formed by the same mechanism(s) and are not compatible with an unconformity.

As well as the mega xenoliths of Magna Lynn Metabasalt within the Leichhardt complex, there are many isolated bodies of the Leichhardt complex within the Magna Lynn Metabasalt. These bodies can be approximately ovoid, circular or lenticular and are commonly 100 m to 500 m in length, with the maximum length in the Blockade block of 900 m (20°34′47″S, 139°54′35″E). Examples are shown in Figures 6, 7 and Figures 9, 10 at A and B. If the boundaries are unconformable, these relationships necessitate a very complex system of doubly plunging folds with variable axial plane orientations. Further, it requires, with local domal antiforms and synforms, that the overall form surface is most likely to be flat-lying and sheetlike. This is at odds with isolated sedimentary intercalations in the Magna Lynn Metabasalt, particularly south of Lake Mary Kathleen, which have generally intermediate to steep dips eastwards, with only locally a minimum of 30°. Trend lines within the Magna Lynn Metabasalt are shown in many areas, e.g. Figure 7, and nowhere are they seen to wrap around protrusions of the Leichhardt complex as would be expected if the boundary was an unconformity which was subsequently folded.

An observation has been made of “possible fiamme” within the Leichhardt complex (Hutton & Withnall, 2013), but an alternative interpretation is that they are small xenoliths from the Magna Lynn Metabasalt that have been variably deformed.

FIGURE 13. Field relationships between light-grey, quartz-feldspar porphyry of the Leichhardt complex, and dark blue-grey metabasalt of the Magna Lynn Metabasalt: (A) Creek barrier outcrop showing the boundary and also an isolated body (upper left) of the Leichhardt complex within the metabasalt, 20°34′12″S, 139°47′49″E; (B) Close-up of continuation of (A) showing serrated sharp boundary; (C) Creek exposure, exact location unknown, approx. 21°2′34″S, 139°46′43″E, showing a porphyry with a transitional contact into amphibolite: (D) Contact between quartz-feldspar porphyry of the Leichhardt complex and biotite schist (R. Bultitude, pers. comm., 2018) belonging to a body currently interpreted as an anomalously young dolerite dyke, 20°47′6″S, 139°47′38″E.

Mega Xenoliths or Metadolerite Dykes?

On MARY KATHLEEN east of Lake Mary Kathleen at 20°47′37″S, 139°47′50″E, a 2.1 km-long by 200 m-wide inlier of Magna Lynn Metabasalt has been shown within the Leichhardt complex. In the existing interpretation this would necessarily represent a doubly plunging syncline, but in the interpretation presented here, it is regarded as one of many mega xenoliths of metabasalt. West of this body, a dating site in a mafic rock has yielded an anomalously young U-Pb SHRIMP age of 763 ± 85 Ma (Bierlein et al., 2008; Hutton & Withnall, 2013). This body is in the spillway of Lake Mary Kathleen at 20°47′6″S, 139°47′38″E, and has been interpreted as a metabasalt dyke intruding into the Leichhardt complex (shown as 'Argylla Fm' on current maps). Alternatively, since it has similar contact features to that shown in Figure 13A–C and a similar appearance on images to the body described above, it may also be a mega xenolith. An example of the contact features of this dated body is shown in Figure 13D. It is difficult to explain the young age, unless it represents a very late phase of alteration. It contains a large proportion of biotite schist (R. Bultitude, pers. comm., 2018).

There are numerous elongate, separate NS bodies of Magna Lynn Metabasalt completely surrounded by the Leichhardt complex, with lengths of up to 2 km and widths up to 400 m (e.g. Figures 6, 7; 20°51′5″S, 139°48′5″E). The net effect is to produce a 'shredded' Magna Lynn distribution pattern.

Throughout the Kalkadoon/Leichhardt complex between Figure 6 and 8 km to the west (Figure 1) on MARY KATHLEEN is a network of generally linear mafic bodies which are shown as dolerite dykes. An exception is a 2 km-long body at 20°55′31″S, 139°43′43″E, which is interpreted therein as Magna Lynn Metabasalt. Some of the larger bodies are up to 400 m wide and 3 km long. These wider bodies are locally crisscrossed by dykes approximately 15 m wide, and are interpreted herein as residual mega xenoliths of Magna Lynn Metabasalt (Figure 1).

Kalkadoon Granodiorite Relationships with the Magna Lynn Metabasalt

Boundaries between the Kalkadoon Granodiorite and the Magna Lynn Metabasalt constitute only a small proportion of the contacts compared with the Leichhardt complex (e.g. Figures 6, 7). On MARY KATHLEEN, only a few km of this boundary are shown. With reinterpretation of many of the more massive dolerite dykes as mega xenoliths of Magna Lynn Metabasalt, these boundaries become much more extensive. An example of the contact between amphibolite, which is interpreted as Magna Lynn Metabasalt and Kalkadoon Granodiorite, is shown in Figure 14.

FIGURE 14. Leucogranite dyke of the Kalkadoon suite intruding metabasalt of the Magna Lynn Metabasalt. The leucogranite contains a xenolith of amphibolite at lower left; 20°45′50″S, 139°41′34″E.

This is interpreted as showing an intrusive relationship between a dyke of the Kalkadoon Granodiorite and the Magna Lynn Metabasalt. Alternatively, it has been suggested that the dyke could simply be part of a suite of granites known to be younger than the Magna Lynn Metabasalt. Arguments against this are that the surrounding intrusion has been mapped as Kalkadoon Granodiorite, and that the closest younger granite to this site (with an age of 1777 Ma) is the Bowlers Hole Granite which is 30 km to the SSE (Figures 11, 12).

Discussion

Interpretations of Previous Mapping

In the MARY KATHLEEN mapping by Derrick et al. (1977), the boundaries between the Leichhardt "Volcanics" and the Magna Lynn Metabasalt were mostly shown as unfaulted and interpreted as conformable or disconformable (e.g. Figures 6, 7). Faulted boundaries were relatively uncommon and mostly restricted to the NNW-SSE extensional set. In the subsequent mapping by Blake (1991), additional fault boundaries are much more common and are shown as meridional thrusts located mainly on the eastern sides of blocks of Magna Lynn Metabasalt. In this way, blocks were interpreted as variably sized thrust slices rather than mega xenoliths as advocated in this study.

An alternative suggestion for the relationships between the Leichhardt complex and the metabasalt in this area and surrounding areas is that they are coeval. This requires that the unit that has been mapped in MARY KATHLEEN (Blake, 1991; and this study) is not Magna Lynn Metabasalt at all, but an intercalation within the Leichhardt Volcanics. Furthermore, it does not explain bedding in the metabasalt at a high angle to the boundary. The irregular shapes and serrated boundaries of metabasalts described above mitigate against this viewpoint and seem more in accord with a residual mega xenolith origin. Most mafics within the Kalkadoon/Leichhardt complex on existing maps are shown as intrusive metadolerites and metagabbros.

Thickness and Extent of the Magna Lynn Metabasalt

The maximum thickness of the Eastern Creek Volcanics has been estimated at 8 km (Wilson et. al., 1984, Figure 1; Bain et al., 1992). The previously published estimated thickness of the Magna Lynn Metabasalt ranges from 200 m to 700 m (Derrick et al., 1977). The belt of metabasalt which contains sufficient sedimentary intercalations south of Lake Mary Kathleen (Figure 1) has been used here to estimate thickness. West of this belt, the unit is interpreted to extend at least a further 8 km, but the structure is unknown, so an estimate of stratigraphic thickness cannot be made. Using the interpretation herein that the mapped distribution of the Magna Lynn Metabasalt represents 'remnants' subsequent to intrusion by the Leichhardt and Kalkadoon units, and an estimate of average dip from sedimentary intercalations of 50°E, the following estimates of minimum stratigraphic thickness were obtained (relative Lake Mary Kathleen, Figure 1): 10.5 km south, 5.6 km; 20.5 km south, 5.5 km; 30.5 km south, 5.2 km. These thicknesses are nearly an order of magnitude greater than the estimates of Derrick et al. (1977) and reflect the difference in measurement between an interpreted unconformity or intrusive origin for the Leichhardt/Magna Lynn Metabasalt boundary.

Rift-controlling Structures?

In the existing interpretations, there has been considerable discussion of rift-controlling structures for the Eastern Creek Volcanics. The normal controlling faults were reckoned to be the Quilalar and Gorge Creek Faults in the east, and the Mount Isa and Mount Gordon Faults in the west (e.g. see Hutton & Withnall, 2013). These structures all appear to be better interpreted as post-Haslingden Group. No controlling structures were advocated for the Magna Lynn Metabasalt to the west. In the interpretation of this study, with the Eastern Creek Volcanics being correlated with the Magna Lynn Metabasalt (discussed elsewhere), no rift boundaries are obvious. To the east, the relationships of the Magna Lynn Metabasalt are obscured by the interpreted intrusion of the voluminous Argylla Formation.

Previous Correlations of Mafic Units

Carter et al. (1961) correlated the Eastern Creek Volcanics and Marraba Volcanics which they regarded as forming east and west of a "tectonic welt". The mafic volcanics in the Cloncurry area (now the Toole Creek Volcanics) were also regarded as being correlative. Bultitude & Wyborn (1982) correlated the Oroopo Metabasalt, Eastern Creek Volcanics and Magna Lynn Metabasalt. Bultitude (1984), in Blake et al. (1984), correlated the Oroopo Metabasalt, the Jayah Creek Metabasalt and the Eastern Creek Volcanics. Blake (1987) interpreted the Eastern Creek Volcanics and the Magna Lynn Metabasalt as being equivalents, with the Marraba Volcanics being significantly younger. In GSQ 2011, all mafic units are shown as having different ages (Figure 2). In summary, all mafic units at various stages could be regarded as correlated.

Dykes in the Granites and Leichhardt Complex

There appear to be up to four sets of dolerite dykes traversing the Kalkadoon Granite/Leichhardt complex and Magna Lynn Metabasalt. These have been interpreted to be younger than these enclosing units. Alternatively, they may represent 'residual' dykes in the Magna Lynn Metabasalt mega xenoliths following advanced overprinting by Leichhardt complex and Kalkadoon Granodiorite. The dykes appear to penetrate the interpreted mega xenoliths where interspersed with Leichhardt complex without divergence, giving the impression that they were in existence prior to the interpreted Leichhardt volume-preserving overprint. The preservation of the dykes may be related to their coarser grain size than the surrounding mafic volcanics, making them less susceptible to intrusion.

Mode of Formation of the Kalkadoon-Leichhardt Complex

It is possible that the intrusive relationships interpreted here instead represent a metasomatic overprint on original unconformities. However, it is difficult to see how such a process could 'mask' unconformities over such a broad area. Another possibility is that there is an older (~1850 Ma) suite intruded by a younger post ~1760 Ma intrusive margin for which no dating exists. A dating site in the Leichhardt complex (1864 ± 3 Ma; Carson et al., 2011, p. 76) (Figures 9, 10 herein) is 10 m from a projection of Magna Lynn Metabasalt. This example would require a very thin, younger phase of the Kalkadoon/Leichhardt complex overlying the older phases.

Conclusions

It is proposed that the origin and relative timing of the Kalkadoon-Leichhardt complex is not clear cut, and that intrusion into the Magna Lynn Metabasalt best accords with the field and image evidence. The current universally accepted interpretation has the boundary as an unconformity, with an estimate of 50 million years of separation before deposition of the Magna Lynn Metabasalt.

Where observed, the boundary is sharp and serrated, and at one locality makes a gross angle of 40 degrees with the strike of a quartzite within the Magna Lynn Metabasalt. Within the metabasalt are zones of quartzofeldspathic metasomatism which appear to be incipient formation of the Leichhardt complex. Most obviously within the Leichhardt complex is a well-developed system of dolerite dykes, and these are interpreted to be residuals following intrusion of the metabasalt. Less-continuous and thicker bodies of metabasalt are interpreted as residual *in situ* relict mega xenoliths following intrusion by the Leichhardt complex.

This interpretation brings into question the relationship of the Kalkadoon/Leichhardt system and the other sequences of metabasalt, namely the Oroopo Metabasalt, the Eastern Creek Volcanics and the Marraba Volcanics. However, unlike the Magna Lynn Metabasalt, there is a series of isotopic dates (mainly maximum depositional ages) which appear to support the 'basement' interpretation for the Kalkadoon/Leichhardt system (e.g. see Hutton & Withnall, 2013).

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Disclosure Statement

No potential conflict of interest was reported by the author.

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Author Profile

Bill Perkins worked as a geologist with Mount Isa Mines Limited and its related companies from 1968 to 1996, in various roles including mining, exploration and research. In 1997 he published the seminal work from his PhD thesis on the origin of the Mount Isa lead-zinc orebodies. This paper advocated a completely different timing of formation of the deposit from the prevailing view. Bill joined the Geological Survey of Queensland, beginning with a mapping program in 2006 and concentrating on the Kalkadoon/Leichhardt Belt. This paper reports on part of this work. He still works for the Survey as a volunteer.

Perinatal Health Surveillance: A Spatiotemporal Analysis of Administrative Health Records from Queensland, Australia, 2008–2018

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Abstract

Research into the spatial and temporal distribution of perinatal health across Queensland, Australia, remains limited. This is despite studies within perinatal epidemiology supporting the importance of exploring spatial trends to identify the geographical distribution of vulnerable groups requiring intervention or further research. The purpose of this study was to explore spatial and temporal trends in perinatal health and antenatal service utilisation across Queensland, Australia. Space-time pattern mining and spatial autocorrelation geographic information system methods were used to analyse administrative perinatal records collected between 2008 and 2018. Changes in perinatal health and antenatal service utilisation over space and time were reported. Areas in *Remote* and *Very remote* parts of Far North Queensland with increasing birth rates over the study period were also identified as hot spots for high proportions of low birthweight births and smoking during pregnancy. Both remote and regional areas of northern Queensland were hot spots for high proportions of public antenatal care visits, while hot spots for private visits were in *Major cities*. This small-area exploration of perinatal health highlights the value of administrative records in monitoring location-based perinatal health outcomes and service use. This can be crucial in monitoring perinatal indicators over time, exploring associations between maternal environment and health outcomes, tracking the impact of health interventions, and identifying marginalised groups.

Keywords: GIS, space-time, perinatal health, emerging hot spot

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Introduction

Where we live influences our health. Spatial and temporal analysis of small-area data plays a crucial role in understanding and monitoring local trends in population health, developing targeted health interventions, and prioritising the allocation of health resources (Wang, 2020). The state of Queensland covers an area of just under 1.5 million square kilometres with an estimated population of over 4 million residents (ABS, 2018a). Located in Australia's north-east, Queensland has over 7000 km of coastline along which over 80% of its population resides. The majority of remaining areas in the state are categorised as *Remote* or *Very remote* based on their relatively limited access to service centres (Figure 1) (Queensland, 2019a).

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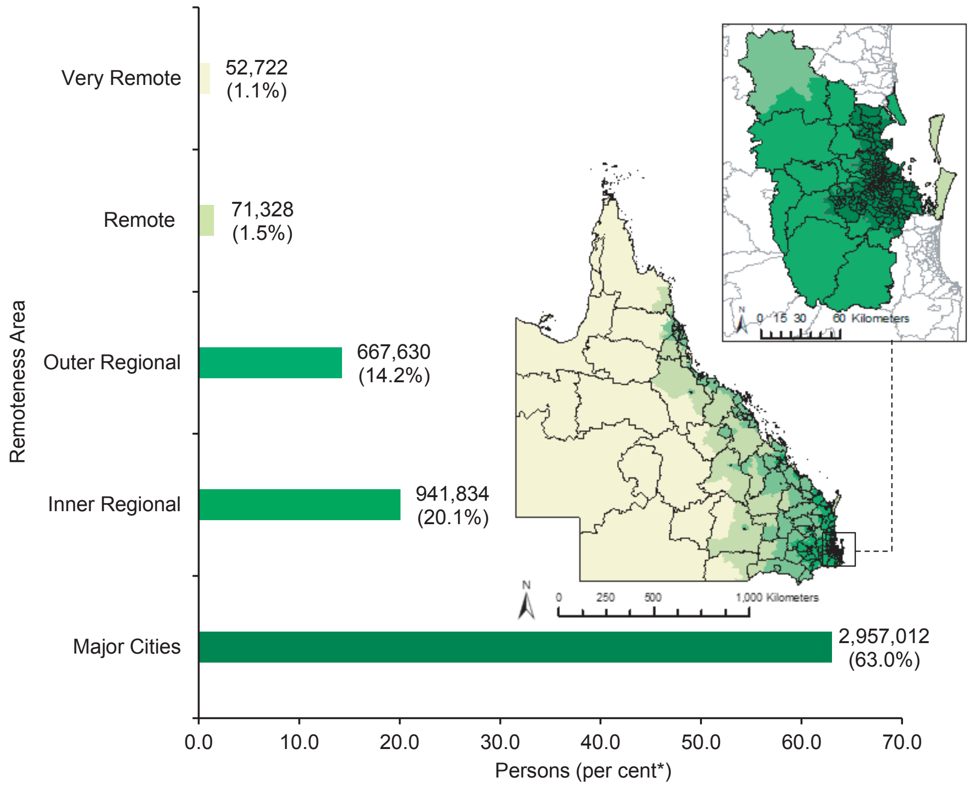

FIGURE 1. Bar graph presents Queensland 2016 population by Remoteness Area. Map inset presents Queensland 2016 Remoteness Areas and 2016 Statistical Area 2 census area boundaries in Greater Brisbane. *Data Source:* Author analysis of ABS 2016 Census TableBuilder.

* Percentages calculated as a proportion of total population by place of usual residence (excludes Migratory-Offshore-Shipping and no usual address).

Queensland's geographical variation in population distribution and remoteness limits the informative value of state-level data. Such data can restrict the identification and monitoring of the health, over time, for smaller populations in remote communities. Once aggregated, their health outcomes are combined with those of larger populations residing in incomparably distinct, and commonly more urban, locations (AIHW, 2022b).

The perinatal period is defined by the World Health Organization (WHO) as commencing at 22 weeks of gestation and ending seven days after birth (WHO, 2022). A mother's location during this period can influence her pregnancy outcomes through her neighbourhood quality (e.g. green spaces, transportation access, availability of core services, condition of buildings/streets, etc.), exposure to extreme weather events, and access and travel time to healthcare providers (Ali et al., 2018). Since 2010, studies using geographic information systems (GIS) to explore maternal health have been on the rise, analysing spatial trends and additional factors such as demographics, socio-economic status, distribution of health services, and education. Examples include an exploration of spatial trends in adverse outcomes such as preterm and low birthweight incidence in Ethiopia (Adeleke et al., 2020), Canada (Seabrook et al., 2019), the United States (Bloch, 2011) and Indonesia (Donal et al., 2018). The relationship between maternal location and antenatal service use has also been studied. Studies exploring greenspace access and perinatal health outcomes in South Carolina, USA (Runkle et al., 2022) and Sydney, Australia (Akaraci et al.,

2021) found an association between maternal location and an increased risk of adverse birth outcomes. A similar association was made between adverse outcome risk and post-natal care usage in Ethiopia, Africa (Sisay et al., 2019). Despite the breadth of existing research, a review of over 5000 articles, at the time of this study, found that most research making use of GIS to explore maternal health came from countries in Africa, Asia, Latin America and the Caribbean (Ahmadian et al., 2020) with limited research originating from Australia.

Perinatal health is measured through both maternal and infant characteristics present during the perinatal period, such as antenatal care provision, maternal behaviour during pregnancy and birth outcomes, all of which can be captured in administrative records. In Australia, consistently collected government administrative health records provide a validated, population-based dataset to analyse small-area perinatal health indicators such as smoking during pregnancy, and preterm and low birthweight births (AIHW, 2022a).

Smoking during pregnancy is a risk factor for miscarriage, low birthweight, premature births, and a wide range of birth defects that have long-term impacts on infant health (Lange et al., 2018). Despite the immediate and long-term health implications of smoking for both the mother and unborn child, 9.2% of Australian mothers were recorded as smoking during pregnancy in 2020 (AIHW, 2022a). Gestational age and infant weight at birth are common indicators of infant mortality and morbidity risk from birth. Within the Developmental Origins of Health and Disease (DOHaD) hypothesis, such indicators can be used to measure and understand the influence of the early life environment, pre- and post-natal, on health and disease risk both at birth and across the life course (Penkler et al., 2019). Infants born prematurely (<37 weeks gestation) or at a low birthweight (<2500 grams) are at an increased risk of higher mortality and morbidity at birth and in later life. They have also been found to be at an increased risk of developing chronic non-communicable diseases in adulthood (de Mendonça et al., 2020). Low birthweight births in an Australian Aboriginal community in the Northern Territory, for example, were found to be at a higher risk of later-life natural deaths, particularly cardiovascular and renal deaths, than non-low birthweight births (Hoy & Nicol, 2019). Similarly, low birthweight babies in the same communities were found to have a higher risk of cardiovascular disease hospitalisations in adult life (Arnold et al., 2016).

Access to appropriate antenatal care throughout pregnancy is associated with reduced complications as it involves regular screening for sexually transmitted infections, high blood pressure and gestational diabetes while monitoring for potential high-risk behaviours such as smoking during pregnancy (WHO, 2012). Communities in *Remote* and *Very remote* areas of Australia face location-based vulnerabilities. This is driven by barriers to accessing consistent and holistic (specialty and general) health services when compared to more urban areas, which can increase the risk of adverse health outcomes (AIHW, 2022a). Informed planning for perinatal health over space and time is crucial to mitigate this ongoing societal and locational disparity. Australian healthcare policy has long acknowledged the importance of geography and population characteristics when evaluating health outcomes. Ongoing health strategies have engaged with sector experts, researchers and policy makers to support equitable access to maternity and birthing services for the vulnerable. They have additionally focused on outcomes within communities and factored in geographic characteristics such as remoteness, socio-economic status and links to medical specialists (Pilcher et al., 2014). This study aims to apply spatiotemporal analytical methods using administrative health records to highlight significant perinatal health trends over space and time in the state of Queensland. Analysing spatial clustering of perinatal health and antenatal care service use will help identify areas for targeted region-specific health service interventions and further research that would support ongoing development of effective perinatal healthcare provision.

Materials and Methods

Study Sample

The Queensland Perinatal Data Collection (QPDC) is a population-based, cross-sectional dataset that includes data items that comply with the Perinatal National Minimum Data Set (P-NMDS) managed by the Australian Institute of Health and Welfare (AIHW). P-NMDS guidelines support consistent collection of data on births in each state and territory. The QPDC monitors patterns of obstetric and neonatal practice across the state, providing statistical information to service providers, policy developers and researchers. The QPDC includes all live births and stillbirths of at least 20 weeks gestation or at least 400 grams in weight (Queensland, 2019c).

Data for 666,803 births collected under the QPDC, from July 2008 to June 2018, where maternal state of usual residence was Queensland, were spatially analysed using STATA statistical software and Esri ArcGis Pro spatial software. The financial period (30 June to 1 July) in which each birth occurred was applied as the time step, and census areas were used to allocate maternal location. Changes in livebirths over time within a census area were explored using crude birth rates. The proportion of preterm and low birthweight births, smoking during pregnancy, and antenatal care provider visits, were used as indicators of perinatal health outcomes and service use (Supplementary Table 1). Antenatal care was defined as a visit between a pregnant mother and a midwife or doctor (AIHW, 2022a). Care providers included midwifery, medical, and general practitioners providing health services for the pregnancy recorded (Table 1). Due to small numbers (cell size of less than 10), incidences of preterm and low birthweight births, and smoking during pregnancy were spatially explored at the Statistical Area 2 (SA2) level using three years of aggregated data (2016–2018).

Table 1. Definitions of antenatal care providers and perinatal health indicators as reported by the Queensland Perinatal Data Collection. Adapted from (Queensland, 2017b).

Data item	Definition
Antenatal care providers	
Midwifery practitioner – Public hospital/clinic	Includes public hospital clinics, hospital-based midwifery clinics and community-based midwifery programs run by nursing staff.
Medical practitioner – Public hospital/clinic	Includes hospitals and hospital-based clinics attended by medical staff.
Medical practitioner – Private – General practitioner	Includes medical officers in a general practice.
Medical practitioner – Private – Specialist	Includes a private specialist medical practitioner in their own private practice (e.g. private obstetrician).
Midwifery practitioner – Private	Includes registered midwives practising in the community.
Perinatal health indicators	
Preterm	Liveborn singleton births at less than 37 weeks gestation as a proportion of the total liveborn singleton births from July 2016 to June 2018.
Low birthweight	Liveborn singleton births weighing less than 2500 grams as a proportion of the total liveborn singleton births from July 2016 to June 2018.
Smoking during pregnancy	Mothers who smoked at any point during a pregnancy as a proportion of mothers with a stated smoking status.

Geographical Concordance

Census-based geographical areas are frequently used in the spatial analysis of population data within perinatal epidemiology such as by Bloch et al's 2011 study into preterm birth disparities across the state of Philadelphia in the USA. In our study, births were assigned to a location using maternal usual residence collected in the QPDC as Statistical Local Area (SLA) census areas until 2011–2012 and updated to Statistical Areas level 2 (SA2) census areas from 2012–2013 onwards (Supplementary Table 2). SA2s and SLAs were coded as defined by the ABS Australian Statistical Geography Standard (ASGS) and the Australian Standard Geographical Classification (ASGC), respectively (ABS, 2010, 2016).

SA2s represent communities that interact together socially and economically with a population range of generally 3000 to 25,000 persons[a] (ABS, 2016). For comparisons over space and time, all births recorded in both SLAs and SA2s were concorded to the same ASGS 2016 SA2 census areas. Concordances are a mathematical method of reassigning data from one geographic region to another region. The ABS produces publicly available concordance files developed using population-weighted grids (ABS, 2012b). This study made use of population-based birth records aligning with the population weighting of applied concordance. Researchers proceeded with data concordance as the ABS public release of associated files deemed the concordance of an acceptable overall quality (ABS, 2012a).

Spatial Autocorrelation

To identify point-in-time spatial clustering of perinatal health indicators, spatial autocorrelation was applied using Global Moran's I and Getis-Ord G_i* statistics. A method previously used in exploring spatial patterns in maternal and child healthcare utilisation across distinct regions in Ethiopia (Defar, Okwaraji, Tigabu, Persson, & Alemu, 2019). Global Moran's I measured the degree of spatial correlation between adjacent SA2s by analysing both SA2 location and recorded data (births). A Moran's I score of 0.3 or more indicated significant positive spatial autocorrelation supporting the non-random clustering of SA2s with similar values. The Getis-Ord G_i* statistic allowed for the point-in-time visual presentation of significant SA2 clusters of high or low values. The p value and z-score developed a G_i score used to thematically map hot and cold spots of significantly clustered areas. Whereby hot spots indicated significant clustering of similar data values and cold spots were indicative of significant dispersion of data across neighbouring SA2s.

Space-time Pattern Mining

To explore changing patterns in birth rates over time, space-time pattern mining methods were applied, as was done by Naqvi et al. (2021) in their spatiotemporal investigation of Dengue Fever in Pakistan and as used by Nielsen et al. (2019) in their exploration of small for gestational age and low birthweight births in Alberta, Canada. SA2s were entered as the location ID, the time step was set as financial year, and the bin data value was set as the crude rate of livebirths per 1000 estimated resident population (ABS, 2012c). Commonly, space-time mining includes the aggregation of point data to determine significant clustering as done in referenced studies; however, to accommodate administrative population data grouped by census areas, a space-time cube (Supplementary Figure 1) was created from defined locations in ArcGIS Pro using SA2 polygons and birth rate per year to create a network Common Data Form (netCDF) file (Esri, 2019a). The netCDF file was imputed into the ArcGIS Pro Emerging Hot Spot Analysis tool which analysed changes in annual birth rates using a space-time implementation of the Getis-Ord G_i* statistic. A spatial relationship between neighbouring SA2 polygons was determined using *contiguity edges only* to factor in the variable sizes of SA2 polygons. The global value was set using individual time steps so each SA2 birth rate was analysed in comparison to the space-time bins in the same time step. Analysis outputs presented a two-dimensional representation of emerging hot and cold spot trends analysed using the Mann-Kendall trend statistic to run rank correlation analysis for birth rates in respective time periods. The trend for each bin series was recorded as a z-score and p value. A positive z-score supported an increase in birth rates, a negative z-score indicated a decrease in birth rates over time, and a low p value (<.05) supported a statistically significant trend (Esri, 2019b).

Results

Birth Rates and Perinatal Health

Significant emerging hot (increasing trend) or cold (decreasing trend) spots in birth rates were reported in 143 of 510 mapped Queensland SA2s between 01 July 2008 and 30 June 2018. Overall, there was a trend of decreasing birth rates across Queensland SA2s from 2008 to 2018 (z-score = –3.94, P<.001) (Table 1). Of the 69 emerging hot

[a] SA2s can fall out of this target population range due to sparse populations in remote areas spread over large and geographically diverse regions, isolated areas such as islands, and arbitrary subdivisions such as large suburbs or regional towns (ABS, 2016).

spots of increasing birth rates, the majority (>50%) included SA2s in *Remote* and *Very remote* areas of northern Queensland, areas along the state's coastline, and in the state capital of Brisbane (Figure 2). Persistent, sporadic, and consecutive trends were indicative of areas where births rates were relatively stable (consistent rates over time), while new, diminishing and intensifying trends highlighted areas with significant changes in birth rates over time (Table 2, Supplementary Table 3).

Table 2. Results of emerging hot spot analysis (neighbourhood time step) of births per 1000 estimated resident population. Queensland, Statistical Area 2, 01 July 2008 to 30 June 2018.

Space-time trend	Hot spots	Cold spots
New	6	4
Consecutive	19	21
Intensifying	2	2
Persistent	16	9
Diminishing	4	5
Sporadic	22	33
Oscillating	0	0
Historical	0	0
Total	**69**	**74**

Although areas in northern Queensland had significant hot spots for high birth rates relative to surrounding SA2s, birth rates in individual SA2s decreased over the time of this study. For example, Cape York's birth rate decreased from 17.3 to 13.3 births per 1000 population. The same areas with emerging hot spots for high birth rates also had hot spots for high proportions of low birthweight births (Figure 3a & 3b), preterm births (Figure 3c & 3d) and smoking during pregnancy (Figure 3e & 3f) in 2016–2018.

The largest increase in birth rates was recorded in Newtown, Toowoomba, up from 17.6 to 37.0 births per 1000 population (Figure 2). In 2016–2018, Newtown was part of a significant hot spot cluster for high proportions of low birthweight and preterm births, recording 7.1% and 10.0%, respectively (Figure 3a & 3c). Toowoomba also had new hot spots identified in Wilsonton and Toowoomba-West SA2s. Despite having no significant trends in birth rates over time (Figure 2), Redland Islands off the coast of Greater Brisbane, classified as *Remote* (Figure 1), presented a significant hot spot for high proportions of all three perinatal health indicators: low birthweight births (Figure 3b), preterm births (Figure 3d), and smoking during pregnancy (Figure 3f).

Overall, the distribution of perinatal health indicators varied across Queensland SA2 areas in 2016–2018. Significant clustering of preterm (Moran's I=0.19, z-score=6.11, P<.001) and low birthweight (Moran's I=0.11, z-score=3.55, P<.001) births was supported throughout the state. Palm Island off the coast of Townsville recorded the highest proportion of preterm births (15.0%), and Yarrabah east of Cairns recorded the highest proportion of low birthweight births (13.0%). Significant hot spot clustering of smoking during pregnancy (Moran's I=0.55, z-score=17.31, P<.001) was mainly identified in *Remote* and *Very remote* parts of the state (Figure 1). The highest proportion of smoking during pregnancy was recorded in Kowanyayama-Pormpuraaw (59.4%) in Far North Queensland (Figure 3).

Antenatal Care Providers

From 2008 to 2018, women giving birth in Queensland had over one million recorded antenatal care visits during pregnancy, which varied over space and time. During this time, public providers made up the highest proportion of reported antenatal care providers, with an increase in public midwifery practitioners from 26.9% to 35.9% of antenatal care visits in 2017–2018 (Figure 4).

In 2016–2018, combined antenatal care visits followed a similar pattern, with public antenatal care providers making up the highest proportion of care used by mothers (66.1% of recorded antenatal care use over the period). Private general practitioners continued to make up the largest proportion of private antenatal care used (Supplementary Figure 2). Spatially, significant clustering of high proportions of *public midwifery practitioner* use occurred in *Remote* and *Very remote* areas of Queensland and Stradbroke Island off the coast of Greater Brisbane (Moran's I=0.46, z-score=15.94, P<.001), while high proportions of *private general practitioner* use had significant hot spot clusters in the capital Greater Brisbane area (Moran's I=0.69, z-score=20.73, P<.001) (Figure 5).

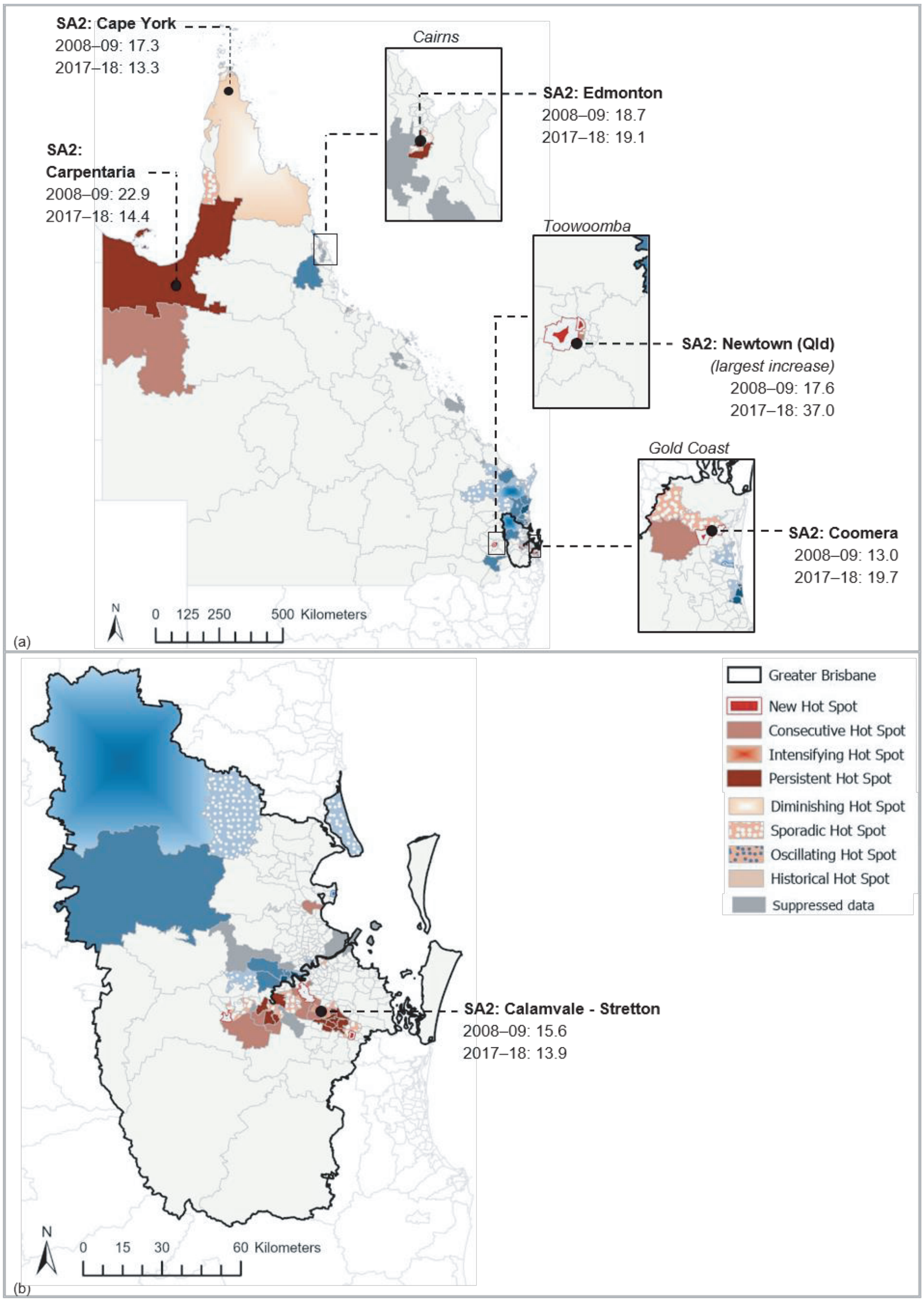

FIGURE 2. Statistical Area 2 (SA2) emerging hot spot analysis of crude birth rate (livebirths per 1000 estimated resident population) from 01 July 2008 to 30 June 2018 in Queensland with (a) state and (b) greater capital city, Greater Brisbane, results (*n=603,845*). Data suppressed where estimated resident population less than 1000 or number of births less than 100. *Data Source*: Queensland Perinatal Data Collection, 01 July 2008 to 30 June 2018.

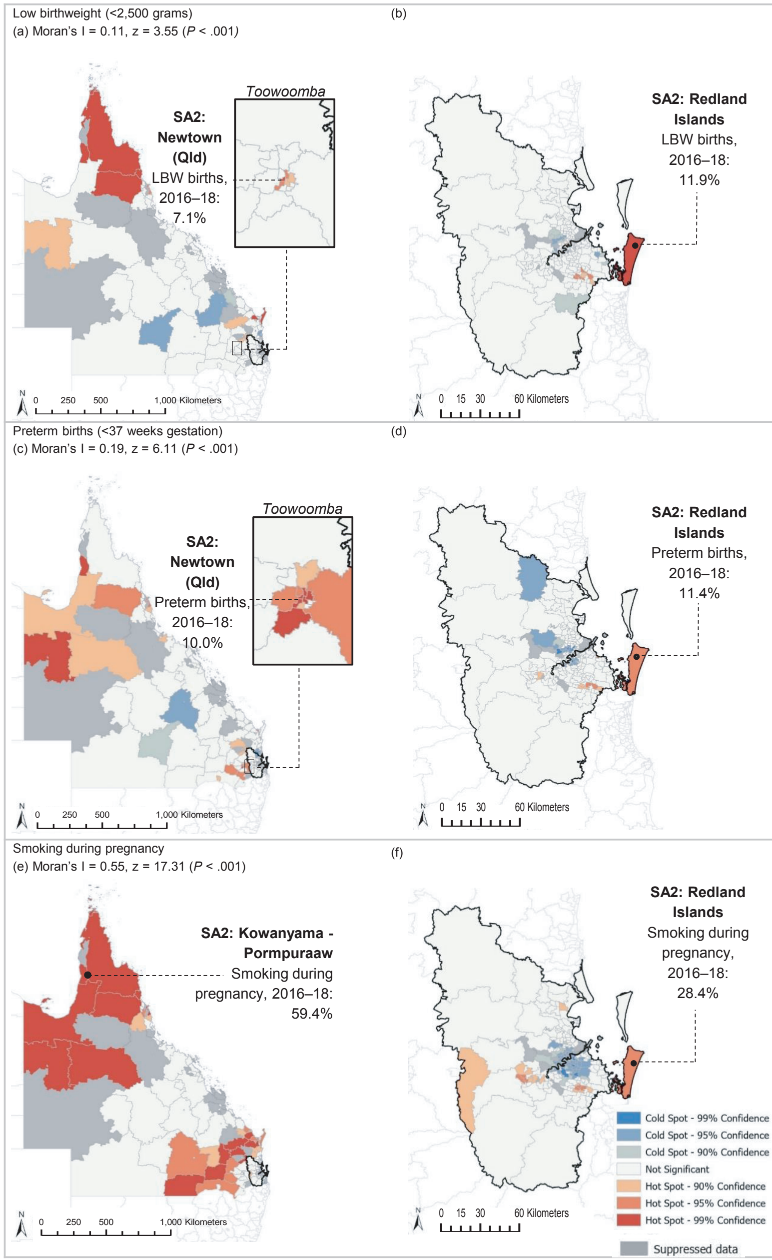

FIGURE 3. Getis Ord G_i* hot spot analysis output maps for Queensland and Greater Brisbane by Statistical Area 2 census areas between 2016 and 2018 for: (a) and (b) low birthweight births (<2500 g) as a proportion of singleton livebirths where weight at birth known (n=9138); (c) and (d) preterm births (<37 weeks gestation) as a proportion of singleton livebirths where gestational age known (n=12,025); (e) and (f) smoking during pregnancy as a proportion of mothers where smoking status during pregnancy known (n=17,020). Data suppressed where number of singleton livebirths or mothers with recorded smoking status during pregnancy less than 100. *Data Source*: Queensland Perinatal Data Collection, 01 July 2016 to 30 June 2018.

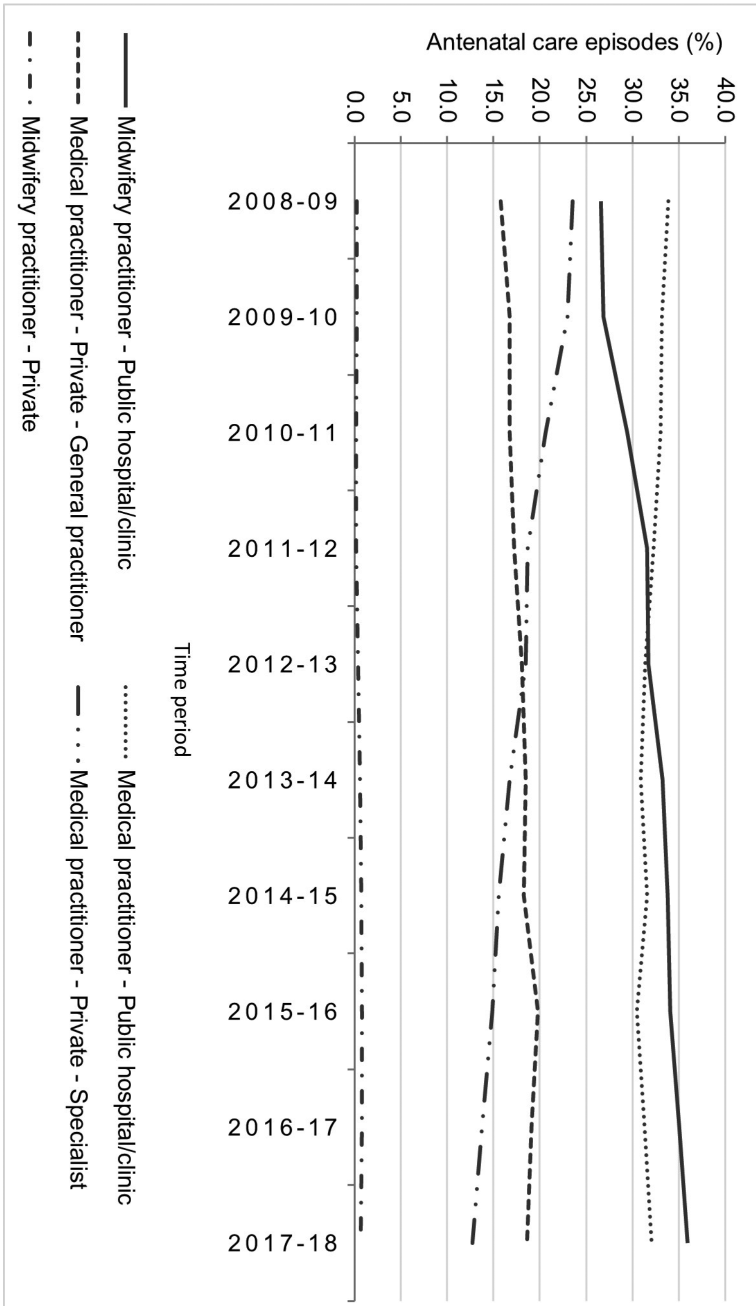

FIGURE 4. Recorded antenatal care visits in Queensland from 01 July 2008 to 30 June 2018 by service provider. Recorded antenatal care providers presented as a proportion of total births where antenatal care provider known. Most antenatal care was sought from public healthcare providers and, over the study period, use of public midwifery practitioners and private general practitioners increased (n=1,951,309). *Note*: A mother can seek support from different antenatal care providers during the same pregnancy.

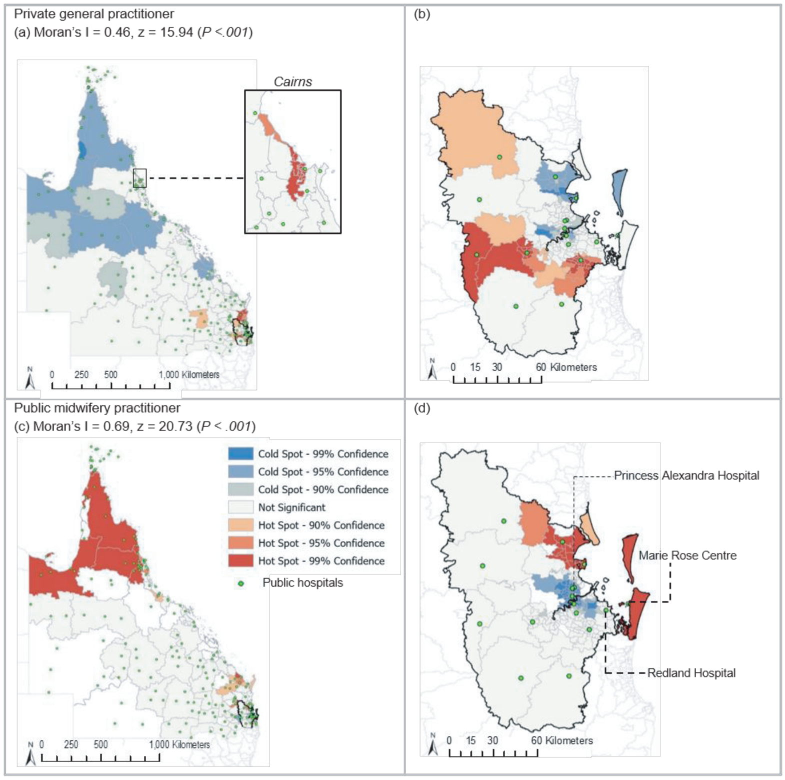

FIGURE 5. Statistical Area 2 (SA2) Getis Ord G_i* hot spot analysis of 'Medical practitioner – Private – General practitioner' (a) and (b); and 'Midwifery practitioner – Public hospital/clinic' (c) and (d) antenatal care providers as a proportion of all stated providers in Queensland between 2016 and 2018. Hot spots for high proportions of 'Medical practitioner – Private – General practitioner' identified in *Inner* and *Outer regional* areas and *Major cities*, *n*=22,816. Hot spots for high proportions of 'Midwifery practitioner – Public hospital/clinic' identified in *Remote* to *Very remote* areas of Queensland, *n*=50,642. *Data Source*: Queensland Perinatal Data Collection, 01 July 2016 to 30 June 2018.

Discussion

The crude birth rate for the state of Queensland has decreased from 15.0 per 1000 population in 2008 to 12.4 in 2018 (ABS, 2019a). Using space-time pattern analysis for the first time on Queensland perinatal data, this study identified areas with increasing birth rates over time (emerging hot spots) and point-in-time hot spots for high proportions of poor perinatal health outcomes. The Toowoomba region exemplified a pattern of increasing birth rates and clustering of poor perinatal health. The region had the largest increase in birth rates in the Newtown SA2 and hot spots identified in Wilsonton and Toowoomba-West. SA2s in Toowoomba were found to have significant hot spots of high proportions of low birthweight and preterm births. This overlap in increasing birth rates and high proportions of low birthweight and preterm births is important when looking at maternal and health service characteristics within these regions. The city of Toowoomba is situated roughly 110 km west of Brisbane, with a population of approximately 100,000 people and another 150,000 living in the surrounding regional and remote areas. Public records list two maternity hospitals that service the area, one publicly funded and the other privately (Brodribb et al., 2007). Remoteness and population movement between the city and regional/remote areas could partly explain these observed patterns in birth rates and perinatal health identified for Toowoomba in this study. This would align with findings from a study using emerging hot spot analysis to explore adverse birth outcomes in Alberta, Canada, which found a spatially significant association between outcomes and environmental factors such as having less access to service centres (Nielsen et al., 2019). More research is needed to examine other location-based health determinants that could be driving the findings of this study. Such determinants could include clustering of demographically vulnerable groups, area-specific population changes over time, and the community's access to antenatal care services.

The types of services offered in any location are affected by local government policy, the availability of healthcare personnel, and access to resources (Eley & Baker, 2007). Increasing remoteness can present a notable geographical barrier to accessing health services by influencing decisions around healthcare engagement and selection of service providers (Ali et al., 2018). Internationally, studies into perinatal epidemiology have highlighted the importance of the location of healthcare providers during pregnancy. This has been found to be particularly important in identifying barriers to care such as travel time, number of appointments (more appointments required in high-risk pregnancies) and associated transport costs for low-income mothers (Bloch et al., 2018). Though reports exist into maternal access to care services in Australia (AIHW, 2017), none have focused specifically on the spatiotemporal distribution of antenatal care use in Queensland. In the current study, high proportions of public antenatal care providers were clustered in *Remote* and *Very remote* areas of Far North Queensland, northern Greater Brisbane, and Stradbroke Island, while significant hot spots for private providers were identified in more urban (*Inner regional* and *Major cities*) areas of southern Greater Brisbane and Cairns. In 2018–2019 there were 692 public hospitals across Australia, 26% of which were in *Major cities*, 58% in *Inner* and *Outer regional* areas, and 16% in *Remote* and *Very remote* areas (AIHW, 2020). Beyond bricks-and-mortar healthcare providers, mothers in remote Australia have access to mobile healthcare services through the public healthcare system. Public hospitals such as Normanton Hospital in remote north Queensland listed outreach services that included the Royal Flying Doctor Service, Mobile Women's Health Clinic and a Flying Obstetrician/Gynaecologist bringing antenatal care services to remote mothers (Baker & Butlini, 1991; Queensland, 2019a; RFDS, 2018).

Mothers receiving antenatal care in Queensland have the option to receive support from a public or private antenatal care provider. More antenatal care visits during pregnancy have been associated with better perinatal outcomes (Health, 2021). Current national guidelines recommend that a mother has their first antenatal visit within the first 10 weeks of pregnancy, and the number of appointments after this is determined based on the mother's needs (Health, 2021). State-specific research into antenatal care use, however, remains limited to assess the efficacy of antenatal care utilisation and perinatal outcomes. From 2008 to 2018, this study found Queensland mothers were more likely to select public antenatal care providers, with a preference for public midwifery practitioners. Although public antenatal care in Queensland works on a referral model based on a mother's location, ongoing preference for public over private antenatal care can be driven by associated benefits such as free access to specialist doctors, services and baby units, and the ability to choose a preferred hospital, obstetrician or midwife (Queensland, 2019b). Accessing private healthcare providers, on the other hand, can be restricted by a mother's access to private health insurance, her socio-economic status, personal choice, and her location. In 2017–2018, the ABS Patient Experience Survey showed that Australians most likely to report having private health insurance were the least socio-economically disadvantaged (78%) and located in *Major cities* (60%) (ABS, 2019b). This was supported by research focused on Queensland's Toowoomba region that found that mothers attending public hospitals were less likely to have private insurance and more likely to be socially and economically disadvantaged (Hegney et al., 2003).

The World Health Organization (WHO) recommends that all pregnant women should have at least eight contacts with a healthcare provider. This facilitates the uptake of preventative measures, timely detection of risky behaviours, reduces complications and addresses health inequalities (WHO, 2016). Proximity to maternal health facilities (public or private) is crucial for providing women with the resources to support positive perinatal health outcomes. A global review of antenatal care utilisation among pregnant women showed that distance from healthcare facilities, particularly when combined with lack of personal transportation or public transport options, led to a decrease in antenatal care utilisation and the frequency of services used (Ali et al., 2018). In this study, though mothers from Redland Islands had no significant trends in birth rates over time, they were part of a significant hot spot for high proportions of low birthweight and preterm births, and smoking during pregnancy. Redland Islands is a *Remote* area and was identified as part of a hot spot for high proportions of public antenatal care visits. However, the only identified island public hospital, the Marie Rose Centre (Dunwich), listed no maternity services and listed its closest main referral hospitals as Redland Hospital (24 km) and Princess Alexandra Hospital (50 km). Both hospitals were located on mainland Queensland, introducing restricted accessibility and additional travel costs (Queensland, 2017a). Socio-economic status can amplify the impact of geographical barriers on perinatal health due to the costs associated with gaining and maintaining personal transport and covering the cost of public transport use. The majority of areas with identified hot spots for high proportions of preterm and low birthweight births and smoking during pregnancy within this study were also areas categorised in the lowest quintile ranking of relative socio-economic advantage and disadvantage (ABS, 2018b). A spatial analysis of preterm births across Philadelphia found a similar relationship between region characteristics (majority race, poverty, and neighbourhood violence) and increased incidences of preterm births (Bloch, 2011).

Our findings on the spatial association between remoteness, antenatal care use and pregnancy outcomes across Queensland aligned with existing international studies using GIS within perinatal epidemiology. These are studies that have similarly found locations in developed countries where poor perinatal outcomes are occurring in areas where mothers are marginalised by geographical or socio-economic disadvantage. In the United States, lower socio-economic status and living in majority black communities were associated with low birthweight and preterm births in South Carolina (Runkle et al., 2022). In Philadelphia, neighbourhoods characterised by poverty, domestic assaults and gun violence were associated with a higher density of preterm births (Bloch, 2011). Across Baltimore, using density mapping and spatial regression, Galiatsatos et al. (2020) found that maternal smoking during pregnancy increased with tobacco store density and was more likely to be observed in neighbourhoods with lower neighbourhood education. Similar to our findings around the impacts of remoteness on outcomes and prenatal care, Bloch et al. (2018) used interpretative mapping to demonstrate the impact of travel time and bus fare costs on access to care for low-income mothers within urban Philadelphia. In British Columbia, Canada, a study looking into the impact of travel time found that similar vulnerabilities such as adolescent age, substance use and low socio-economic status were prevalent among mothers travelling further (≥60 minutes) for delivery. Furthermore, travel times ≥120 minutes were associated with increased stillbirths and maternal morbidity (Luke et al., 2022). Lower SES neighbourhoods across Southwestern Ontario were found to have higher rates of teenage pregnancies, with teenage mothers also found to be at a higher risk of depression, anxiety and smoking during pregnancy (Wong et al., 2020).

As global and national policy continues to encourage the improvement of maternal and infant health and welfare, the findings of this study highlight the importance of identifying small-area trends in perinatal health to inform future context-based policy and targeted environmental health research. In 1998, the WHO proposed a set of principles for perinatal care that encouraged the protection, promotion and support necessary for effective antenatal and postnatal care to support maternal and infant health. Among these principles was an emphasis on care being local and available as close to a woman's home as possible, and to include an efficient system of referral from primary to tertiary levels of care (Health, 2021). These principles are vital in the context of our study findings that identified significant clustering of low birthweight and preterm births, smoking during pregnancy, and antenatal care visits in Queensland.

Conclusion

There is significant spatial and temporal variation in Queensland's birth rates, perinatal health and antenatal care use. Using geographic information system (GIS) methods to analyse administrative health records allowed for the identification of small-area disparity over time and will support future informed exploration of the drivers of such localised patterns. Antenatal care providers, perinatal health professionals, and policy developers should consider the informative contribution of GIS analysis in perinatal health, particularly when identifying additional vulnerabilities within priority health groups.

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Associate Professor Aparna Lal moved to the ANU as a postdoctoral fellow with the National Centre for Epidemiology and Population Health, working with the Infectious Disease Epidemiology and Modelling group. Her research focuses on how the physical environment, broadly defined, impacts human health and well-being. Her projects combine public health surveillance with remote sensing, and land and water quality monitoring data to quantify, monitor and understand the processes that shape disease patterns. She uses a wide range of techniques to examine research questions, with a focus on spatial models and temporal approaches.

Frequently Burnt Subtropical Eucalypt Forest Is More Resilient to Wildfire Than Rarely Burnt Forest

Paul Williams[1], Penny Watson[2], David Kington[1,3] and Eleanor Collins[1]

Abstract

Open eucalypt forests with a grassy understorey are becoming rare in the volcanic landscapes on the Queensland–New South Wales border, as woody plants thicken with the cessation of regular planned burning. Whether previous planned burning reduced the impact of the 2019 unplanned wildfires on forest condition is debated. We evaluated the role of planned burning on the condition of a subtropical eucalypt forest following a wildfire in 2019. Two years after a wildfire at Mt Lindesay, a section of forest that had been frequently burnt was in better condition than adjacent rarely burnt forest. Specifically, there was significantly greater cover of kangaroo grass and a lower density of tree saplings in frequently burnt forest. The canopy of rarely burnt forest showed more signs of dieback. The pattern of healthier eucalypt forest with frequent burning was observed at other South East Queensland sites, Mt Gillies and Spicer's Gap. These observations suggest long-term frequent burning under mild conditions with good soil moisture maintains grassy eucalypt forest that is resilient to occasional intense wildfires during drought, such as seen in late 2019.

Keywords: planned burning, frequent fire, wildfire, overabundant saplings, kangaroo grass

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Introduction

Eucalypt forests are the predominant vegetation type of the coast and ranges of subtropical eastern Australia. The understorey beneath the trees ranges from low, open and grassy, to a dense subcanopy of trees and shrubs. On the fertile volcanic soils of South East Queensland and north-eastern New South Wales (NSW), tall, straight-trunked eucalypts overtop what was once an understorey of robust native tussock grasses and herbs (Butler et al., 2014; Stone et al., 2018). Cessation of Indigenous fire management has resulted in the thickening of plants promoted by occasional high-intensity fires, especially wattles, and the encroachment of semi-mesic woody plants into these formerly open landscapes, with succession to rainforest possible (Butler et al., 2014; Stone, 2018; Baker et al., 2020). This trend prevails to the point where open eucalypt forests with a grassy understorey are becoming hard to find (Kington et al., 2021; Stone et al., 2022). Encroachment of woody vegetation into once-grassy landscapes due to loss of Indigenous fire management has been documented across Australia (Stanton et al., 2014; Fletcher et al., 2021; Roberts et al., 2021; Chevis et al., 2022; Mariani et al., 2022). Loss of open grassy ecosystems in

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tropical and subtropical landscapes is a conservation issue deserving of much greater recognition than it currently receives (Parr et al., 2014; Bond, 2019). The scarcity of these iconic landscapes is a shame in itself and is also associated with a decline in fauna that use grasses for foraging and shelter (e.g. Stone et al., 2022).

Indigenous fire management in grassy ecosystems generally involved frequent, low-intensity fire, and continues to do so where practised today (Mariani et al., 2022; Steffensen, 2020). Australian ecosystems are also burnt by non-Indigenous Australians, primarily to reduce fuel loads for the protection of life and property, to encourage green pick for stock (Jarman et al., 1987), and for conservation purposes. Planned burning (also called prescribed burning) has been shown to reduce the extent and impact of wildfires, both in Australia (Boer et al., 2009; Price et al., 2012) and overseas (Hunter & Robles, 2020; Santos et al., 2021), although its capacity to do so depends on a variety of factors, including ecosystem type and condition, as well as time since previous fire (Storey et al., 2016). However, the capacity of planned burning to mitigate the effects of wildfire on conservation-related parameters has received little attention.

Large areas of eastern Australia were burnt in unplanned, high-intensity wildfires between August 2019 and February 2020 (Adams et al., 2020; Collins et al., 2021; Smith et al., 2021; Baker et al., 2022). High-intensity wildfires can damage the canopy and kill eucalypt trees which normally survive lower-intensity fires (Williams et al., 2020). They can also promote dense germination of trees and shrubs because the elevated heat penetration into the topsoil breaks the dormancy of hard-seeded species such as wattles and damages roots, promoting stem propagation via root suckering (Williams et al., 2004; Palmer et al., 2018).

Excessive sapling density smothers grasses and herbs in subtropical eucalypt forest (Kington et al., 2021; Lewis & Debuse, 2012; Baker et al., 2020), and it is grasses and herbs that provide the bulk of species diversity in these forests of South East Queensland (Ryan, 2012). The loss of native grass cover reduces the capacity of land managers to implement low-intensity fires under mild conditions, because fire carries through a continuous grass layer while there remains good soil moisture early in the dry season but is less capable of spreading through a ground layer of predominantly leaf litter until soil and fuel dry out (Baker et al., 2021). A forest cluttered with tree saplings has very high to extreme elevated fuel that can increase the intensity of a fire and create a ladder of fuel that burns into and damages the canopy (Barker et al., 2022).

In this study, we investigated whether the impact of a wildfire on a subtropical eucalypt forest could be minimised by prior frequent planned burning. Specifically, we examined adjacent areas of forest with contrasting fire histories, two years after both areas were burnt in the 2019 wildfires, comparing them on the following indicators of forest condition: native grass cover, species richness, density of tree saplings, and canopy health.

Methods

Mt Lindesay

The primary study site lies on the western foot slopes of Mt Lindesay, in Mt Barney National Park, less than 1 km north of the Queensland–NSW border. The vegetation is subtropical eucalypt forest, dominated by *Eucalyptus propinqua* and *E. microcorys*. This forest is classified as Regional Ecosystem 12.8.8a, which has an 'Of Concern' Queensland *Vegetation Management Act 1999* status (Queensland Herbarium, 2021). The broad landscape surrounding the site has a long, continuous history of frequent burning under mild conditions. For four generations the Hardgrave family have implemented a frequent low- to moderate-intensity burning program under mild conditions on their cattle grazing property, part of which became Mt Barney National Park (S. Hardgrave, pers. comm., 6 September 2021); i.e. a continuous frequent burning program has run for more than a century. According to the landholder, this regime continued the regular burning practices of the Indigenous people of the area (S. Hardgrave, pers. comm., 6 September 2021).

Surveys of the influence of frequent burning on the vegetation response to the 2019 wildfire were undertaken on either side of the Mount Lindesay Highway (28.3343°S; 152.7069°E). At this location, the 'highway' is a narrow, winding road running roughly south. The wildfire in late 2019 burnt both sides of the Mt Lindesay Highway in this area, during drought conditions. Due to the highway and another fire break, the western side of the highway had not been burnt for at least 20 years prior to 2019 (D. Kington, pers. comm., 6 September 2021). In contrast, the eastern side of the highway received frequent fire (i.e. every few years) up until 2012, after which there was a hiatus in burning prior to the 2019 wildfire (S. Hardgrave, pers. comm., 6 September 2021). This difference in fire regime and the resulting vegetation condition on either side of the highway have been observed and discussed by two of the authors (D. Kington and P. Watson) for two decades.

On 6 and 7 September 2021, two years after the wildfire, six transects were surveyed: three on the frequently burnt, eastern side of the highway; and three on the rarely burnt western side. As the area of frequently burnt forest was small, the transect positions were not selected randomly but spread out across a 250 m stretch of forest on each side of the highway. In each transect, all woody plants were counted and allocated to size classes, and the percentage cover of grasses and herbs was estimated within 10 evenly spaced 1 m^2 quadrats. The three transects in the frequently burnt area were 50 m long by 4 m wide. The three transects in the rarely burnt area were half that length (i.e. 25 m × 4 m), due to the high density of saplings and tangle of native vines. The woody plant counts in the 25-m long transects were doubled to allow comparison with counts from the 50-m long transects.

The statistical significance of differences between fire histories was assessed using an ANOVA for the density of shrubs and saplings, the percentage cover of native grasses, and species richness per 1 m^2.

Consistency in Vegetation Patterns

Observations were also made at the nearby Mt Gillies section of Mt Barney National Park (28.3057°S; 152.7433°E). This eucalypt forest has received a continuous program of burning every few years for over a century but was not burnt in the 2019 wildfire. This site provided a background example of forest condition with regular burning, in the absence of the 2019 wildfire.

To check the consistency of vegetation response to the 2019 wildfire between frequently burnt and rarely burnt forest, observations were also made in *Eucalyptus dunnii* forest (Regional Ecosystem 12.8.11) at the Spicers Gap section of Main Range National Park (28.081°S; 152.4099°E). Regional Ecosystem 12.8.11 has an 'Of Concern' Queensland *Vegetation Management Act 1999* status (Queensland Herbarium, 2021). This area was a known eastern bristlebird (*Dasyornis brachypterus*) site until a few decades ago.

Results

Mt Lindesay

The frequently burnt eucalypt forest on the foot slopes of Mt Lindesay had an open mid stratum of saplings, with a dense continuous ground layer of native grasses. In contrast, the rarely burnt forest had limited grass cover and excessive saplings after the 2019 wildfire (Figures 1 and 2). Sapling density (<2 m tall) was significantly lower in the frequently burnt than rarely burnt forest ($F_{1,4}$ = 14.16; P <0.02; Figure 3), as was combined sapling density up to 6 m tall ($F_{1,4}$ = 9.155; P <0.04). The most common saplings in both frequently and rarely burnt forest were *Acacia maidenii*, *Allocasuarina torulosa*, *Corymbia intermedia*, *Eucalyptus propinqua*, *Lophostemon confertus*, *Polyscias elegans* and *Trema tomentosa*. The canopy of the rarely burnt forest was observed to clearly have a greater abundance of dead branches than the frequently burnt forest, although this was not quantified.

The cover of the native kangaroo grass (*Themeda triandra*) was significantly higher in the frequently burnt forest ($F_{1,4}$ = 9.622; P <0.04; Figure 4). Blady grass (*Imperata cylindrica*) was more abundant in the frequently burnt forest (mean 15.9% cover in frequently burnt vs 6.4% in rarely burnt forest), and bracken ferns (combined cover of *Calochlaena dubia* and *Pteridium esculentum*) were more common in the rarely burnt forest (2.5% cover in frequently burnt vs 9.1% in rarely burnt forest). However, the differences in blady grass and bracken fern cover between regularly and rarely burnt forest were not statistically significant ($F_{1,4}$ = 62.172; P >0.2 and $F_{1,4}$ = 63.866; P >0.3, respectively). Average species richness per 1 m^2 was similar between fire regimes (6.8 in frequently burnt vs 6.1 in rarely burnt forest, $F_{1,4}$ = 0.395 P >0.5).

FIGURE 1. Frequently burnt eucalypt forest at Mt Lindesay, two years after a 2019 wildfire.

FIGURE 2. Rarely burnt eucalypt forest at Mt Lindesay, two years after a 2019 wildfire.

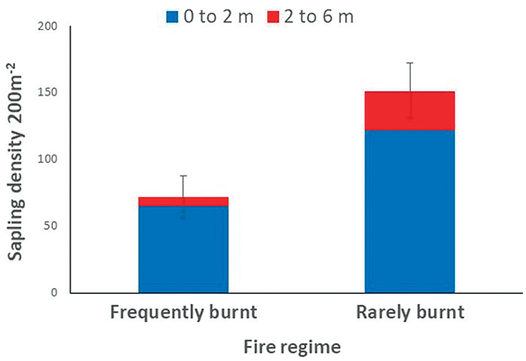

FIGURE 3. Mean sapling density across 200 m^2, at two years after a 2019 wildfire, in frequently and rarely burnt eucalypt forest at Mt Lindesay. Size classes of saplings are shown (0 to 2 m and 2 to 6 m). Error bars are one standard error of the mean, for all saplings combined.

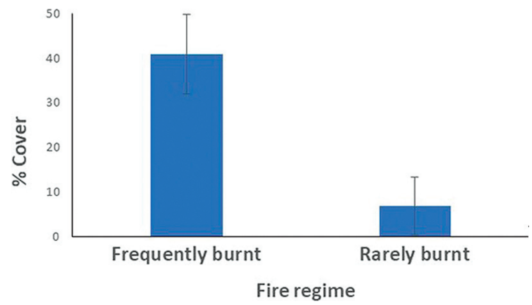

FIGURE 4. Mean percentage cover of kangaroo grass (*Themeda triandra*) in frequently and rarely burnt eucalypt forest at Mt Lindesay. Error bars are one standard error of the mean.

FIGURE 5. Frequently burnt eucalypt forest at Mt Gillies, dominated by kangaroo grass.

Consistency in Vegetation Patterns

The eucalypt forest on nearby Mt Gillies, which has been frequently burnt for at least a century, had a dense cover of kangaroo grass in the ground layer, an open mid stratum with scattered saplings, and a healthy canopy (Figure 5).

Following the 2019 wildfire, the frequently burnt eucalypt forest at Spicer's Gap in Main Range National Park resembled that of Mt Lindesay, in having fewer saplings and a greater cover of native grasses (*Poa labillardierei, Sarga leiocladum* and *Themeda triandra*) compared with adjacent rarely burnt forest (Figures 6 and 7).

FIGURE 6. Frequently burnt eucalypt forest at Spicer's Gap, burnt in 2019 wildfire.

FIGURE 7. Rarely burnt eucalypt forest at Spicer's Gap, burnt in 2019 wildfire.

Discussion

The data set in this study, of six transects at a single location plus visual observations at secondary locations, is limited. The study should thus be seen as an initial exploration of the influence of pre-wildfire fire regime on forest resilience. In this discussion, we will refer to our findings as observations. We consider our conclusions tentative pending further empirical investigation.

The Mt Lindesay transect data and observations at Spicer's Gap provide examples where frequent burning under mild conditions has maintained a healthy, grassy subtropical eucalypt forest that was more resilient to the 2019 wildfires than rarely burnt forest. A long history of regular burning appears to have limited the excessive post-wildfire sapling recruitment seen in rarely burnt forest. Frequent burning also maintained a healthy, dense native grass layer. The observed condition of the vegetation at Mt Gillies and Spicer's Gap was consistent with our findings at Mt Lindesay.

An overabundance of native saplings, especially wattles and eucalypts, is a recognised indicator of unhealthy subtropical eucalypt forests (Williams et al., 2020; Virkki et al., 2021). High-intensity fires promote abundant recruitment of some woody species, especially wattles, other legumes and some rainforest trees (Morrison, 2002; Lewis & Debuse, 2012; Williams et al., 2012; Collins, 2020; Baker et al., 2022). The risk of high-severity fire increases with high elevated fuel loads (Furlaud et al., 2021). For example, in Warrumbungle National Park, the abundance of *Acacia* species increased four-fold after a high-intensity wildfire, with their density positively correlated with fire severity (Gordon et al., 2017; Palmer et al., 2018). The increase in sapling density causes a positive flammability feedback, whereby intense fires promote dense sapling recruitment which, in the absence of regular fire, grows into the mid strata, increasing elevated fuel loads and subsequent fire intensity. This feedback loop has recently been documented in eucalypt forests in Victoria (Karna et al., 2021), providing a mechanism for the recently recognised tendency for high-severity fire to beget further high-severity fire (Barker & Price 2018; Barker et al., 2022).

High sapling density, particularly of nitrogen-fixing wattles, increases soil nitrogen levels, promoting the young, soft eucalypt foliage targeted by psyllids, which is correlated with Bell miner associated dieback of subtropical eucalypt forests (Wardell-Johnson et al., 2005). Excessive sapling density also corresponds with a loss of native grasses and herbs in subtropical eucalypt forests (Baker et al., 2020; Williams et al., 2020). The maintenance of a dense native grass cover, especially of *Poa* spp. and *Themeda triandra*, is critical for fauna such as the northern population of the eastern bristlebird (Stone et al., 2018) and the Hastings River mouse (*Pseudomys oralis*; Tasker & Dickman, 2004). Grass abundance is also essential for maintaining the capacity to implement low-intensity fires that carry patchily through the landscape under mild conditions, while good soil moisture remains following the wet season (Simpson et al., 2016; Prior et al., 2017; Padullés Cubino et al., 2018).

In the frequently burnt grassy forest at Mt Lindesay, the lack of a dense mid-storey meant that the flammable understorey was separated from the eucalypt canopy many metres above, reducing the possibility of crown fire. The value of frequent planned burning in reducing both the intensity and the spread of wildfires has been demonstrated across Australia. For example, prescribed burning at intervals of up to five to seven years can minimise wildfire occurrence in eucalypt forests of southern Australia (Volkova et al., 2021). Planned burning under mild, early dry season conditions in northern Australia has successfully reduced the extent of late dry season, high-intensity fires across a vast landscape (Edwards et al., 2021). A study of 52 years of fire history in southern Western Australia found that regular prescribed burning markedly reduced the incidence and extent of wildfire, particularly large fires, and especially in the 1960s when prescribed burning activity was at a maximum (Boer et al., 2009). These results also support the conclusion of a recent international review that regular planned burning lowers the intensity of subsequent wildfires (Hunter & Robles, 2020).

Although the density of saplings in the regularly burnt forest at Mt Lindesay was only half that in the infrequently burnt area, quite a number of saplings were present nevertheless. The seven-year interval before the wildfire had likely allowed some build-up of shrub and tree propagules, which were then triggered to germinate by the wildfire. This area would likely benefit from follow-up fires at intervals shorter than seven years, to ensure mid-storey density does not continue to increase, to the detriment of the grassy understorey. In South East Queensland, current recommended frequency for these very productive forests is 3 to 5 years (Kington et al., 2021).

We conclude that these observations suggest long-term frequent burning in subtropical grassy eucalypt forest, under mild conditions, promoted and maintained a healthy understorey of grasses and herbs, together with scattered saplings. This forest appeared resilient to the damaging effects of the 2019 wildfires. In contrast, adjacent forest that had not received regular fires was damaged by the 2019 wildfires. Thus, these observations suggest regular burning in these grassy forests is not only beneficial for maintaining forest structure and health, it also minimises the impact of wildfire if one does occur during drought conditions.

Further research is required to expand on these observations to better quantify the influence of frequent burning on the condition of grassy eucalypt forests after wildfire. Further investigation would ideally assess pre- and post-wildfire sapling density and tree canopy health, as well as grass abundance and vigour.

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Population Dynamics and Fire Response of Two Rare Shrubs in Brisbane Eucalypt Forests

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Abstract

Understanding how eucalypt forest flora respond to fire allows the implementation of a planned burn program that best suits the ecosystem, including threatened species. We report on the dynamics and response to low-intensity planned burning of two rare shrubs that grow in Brisbane eucalypt forests on metamorphic hills (Regional Ecosystem 12.11.5). A population of the Vulnerable *Notelaea lloydii* at Changing Mountain on the western side of Brisbane has been stable for the last seven years. All plants burnt in low-intensity fires in 2021 survived and rapidly regrew to over half their pre-fire height within a year. However, no seedlings of *N. lloydii* have been seen. The species' Vulnerable status is supported. The Critically Endangered *Zieria gymnocarpa* is restricted to the Belmont Hills area in eastern Brisbane. The numbers of *Z. gymnocarpa* in a 100 m^2 monitoring transect have dropped significantly from 248 in 2015 to only 34 plants in April 2022. The population decline was initially recorded in the dry period between 2015 and March 2016. *Zieria gymnocarpa* regenerated vegetatively after an August 2016 fire via coppice shoots at the base of stems and root suckers. Plant numbers a year after fire were similar to pre-fire density. However, the population has subsequently continued to decline and no seedlings have been seen during any survey. Further assessment is needed to estimate the population density across the species' entire range and to investigate ways to promote its numbers. Given its small distribution and documented decline, we support the Queensland *Nature Conservation Act 1992* status of Critically Endangered and suggest *Z. gymnocarpa* also be listed as Critically Endangered under the Federal *Environment Protection and Biodiversity Conservation Act 1999.*

Keywords: *Notelaea lloydii, Zieria gymnocarpa*, fire management, monitoring, subtropical eucalypt forest

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Introduction

South East Queensland contains nearly a third of Queensland's threatened species, due to the variety of habitats and extent of vegetation clearing (Williams & Clouten, 2021). Appropriate fire and weed management is a critical aspect of conservation land management, including the preservation of threatened species. Monitoring changes in flora abundance over time and their responses to management actions allows ongoing refinements. The purpose of this study was to monitor populations of two rare shrubs of Brisbane eucalypt forests, to observe dynamics over time and their response to planned burning carried out by the Brisbane

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City Council for ecological and hazard reduction purposes.

Notelaea lloydii Guymer, Oleacaeae, is a tall shrub with narrow opposite leaves and black berries (Figure 1; Guymer, 1987). It is endemic to South East Queensland, growing from Somerset Dam to south of Beaudesert (Halford, 1998). A recent assessment found the shrub is threatened by potential clearing for urban expansion and is only known from five locations with 30 or fewer individuals, plus several scattered plants along roadsides (Manwaduge et al., 2020). *Notelaea lloydii* has a Vulnerable status under both the Queensland *Nature Conservation Act 1992* (NC Act) and Federal *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act).

Zieria gymnocarpa (J.A.Armstr.) P.I.Forst., Rutaceae, has a Critically Endangered status under the Queensland NC Act but is not listed under the EPBC Act (Figure 2; Forster, 2020). It is a shrub with warty opposite leaves occurring as 3-leaflets. Crushed leaves have an odour best left unsampled. They have tiny white flowers. *Zieria gymnocarpa* is restricted to a 3.5 km diameter section of eucalypt forest at Belmont Hills and adjacent Mt Petrie, in eastern Brisbane.

The original collection of *Z. gymnocarpa* was at Belmont in September 1887 by J. H. Simmonds (Forster, 2020). The shrub was previously considered a subspecies of the more widely distributed *Z. furfuracea* but was recently upgraded to its own species, *Z. gymnocarpa* (Forster, 2020).

The populations of *N. lloydii* and *Z. gymnocarpa* assessed in this study grow in Regional Ecosystem 12.11.5, which is eucalypt forest on metamorphosed sediments on hills dominated by *Corymbia citriodora* subsp. *variegata* with *Eucalyptus siderophloia*, *E. crebra*, *E. propinqua* and/or *E. acmenoides*.

FIGURE 1. *Notelaea lloydii* at Changing Mountain.

FIGURE 2. *Zieria gymnocarpa* at Belmont Hills.

Methods

Notelaea lloydii and *Z. gymnocarpa* populations have been monitored since 2015, including before and after planned fires, as part of a broader vegetation monitoring program run by the Brisbane City Council. The monitoring began in 2008 and is undertaken in March or April each year (Williams & Collins, 2022). Each transect is 25 m long by 4 m wide (the narrow width is used to help with the accuracy of recounts) and is permanently marked by a post at each end. All woody plants, including seedlings and root suckers, are counted within the transect. A coordinate is recorded for individual woody plants (i.e. a distance along the transect and a measurement out from the central tape), unless they occur in large numbers clustered together. Where many plants are clustered, plant counts are made within segments of the transect – e.g. plants counted between 0 and 2 m along, then between 2 and 4 m along, etc.

Notelaea lloydii plants grow as well-spaced, distinct multi-stemmed shrubs, and the position along and out from the centre of the transect was recorded for each plant. Due to the significance of *N. lloydii* and their scattered distribution, several plants that grow adjacent to the 25 m × 4 m transect were included. *Notelaea lloydii* plants were monitored in three transects at Changing Mountain Reserve, near Lake Manchester, in the west of Brisbane. The locations of transects, plus dates of surveys and recent fires, are presented in Table 1. One of the Changing Mountain transects, Transect 90, has been surveyed in most years since 2015. Transects 108 and 109 were established prior to planned burns in 2021. All three transects were burnt in late July to August 2021, with average scorch heights (i.e. dead leaves from radiant heat) ranging from 2 to 4 m, which is considered low intensity.

Table 1. Transect details, including dates of the most recent fires and of monitoring surveys. "X" indicates a survey in a particular year. All surveys were undertaken in March to April, so that a survey occurred before a burn of the same year. That is, the 2016 survey at Belmont Hills was completed before the 2016 fire and the 2021 surveys occurred before the 2021 fires at Changing Mountain.

Transect No. & Reserve	Latitude Longitude	Recent fire	2015	2016	2017	2018	2019	2020	2021	2022
Notelaea lloydii Transects:										
90, Changing Mountain	27.509865°S 152.778913°E	2021 August	X	X	X	X	X		X	X
108, Changing Mountain	27.508196°S 152.774132°E	2021 August							X	X
109, Changing Mountain	27.505886°S 152.796452°E	2021 July							X	X
Zieria gymnocarpa Transect:										
73, Belmont Hills	27.513324°S 153.124071°E	2016 August	X	X	X	X	X			X

Zieria gymnocarpa was monitored in a single transect at Belmont Hills, which was initially surveyed in March 2015. This transect was purposely positioned within the core population of *Z. gymnocarpa* so that it could provide an indication of population dynamics. These plants grow as small multi-stemmed plants clustered together. Most of these plants were counted within contiguous 2 m segments of the transect, with a precise position along the transect only recorded for large, isolated plants. The transect was burnt in August 2016, producing an average scorch height of 2 m, which is considered a low intensity.

Results

Notelaea lloydii

The only *N. lloydii* plant growing in Transect 109 was not burnt in the July 2021 fire, due to the burn's patchiness, and remained alive in April 2022. Every burnt *N. lloydii* plant in the other two transects (five in Transect 90 and four in Transect 108) survived by regrowing from subsoil coppice shoots emerging from the base of the stems. The regrowth shoots had returned to over half their pre-fire heights within a year of fire (Figure 3). The number of stems per plant increased as a result of the fires. In Transect 90, stem number increased from an average of five per plant to well over 10 stems. In Transect 108, it increased from an average of 3.25 to 5.5 stems. No seedlings of *N. lloydii* have been observed during any survey, including the post-fire surveys, even though mature fruit have been seen.

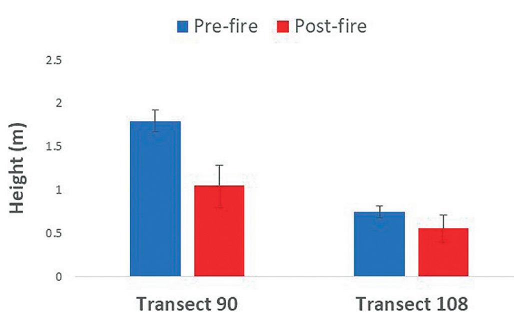

FIGURE 3. The average pre-fire and regrowth height at eight months post-fire (±1 standard error) of *N. lloydii* plants burnt in August 2021.

Zieria gymnocarpa

The numbers of *Z. gymnocarpa* have dropped drastically from their original 2015 count of 248 to only 34 remaining in April 2022 – i.e. only 14% have survived the last seven years (Figure 4). Specifically, *Z. gymnocarpa* numbers dropped from 248 in 2015 to 182 in March 2016, which was one of the driest periods of the last 15 years in Brisbane. *Zieria gymnocarpa* plants regenerated after an August 2016 fire from coppice shoots from the base of the plant and from root suckers away from the original stem base, which caused a drop in plant height (Figures 4 and 5). The *Z. gymnocarpa* population number was roughly stable before the fire (182 in 2016) and a year after the fire (173 in 2017), but the population has further declined steadily since (Figure 4). The surviving plants have not grown beyond their average height at one year after the 2016 fire. While several plants have flowered, no *Z. gymnocarpa* fruit or seedlings have been seen at any time, including after the fire, or during the high rainfall in 2022.

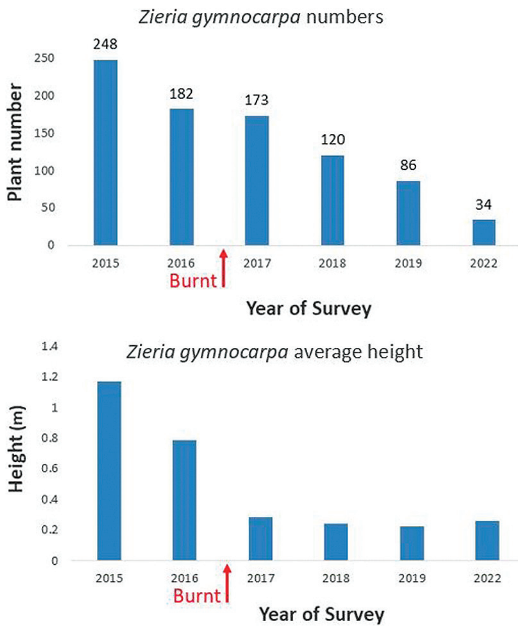

FIGURE 4. The number (top) and average height, ±1 standard error (bottom graph), of *Z. gymnocarpa* in Transect 73 at Belmont Hills.

FIGURE 5. *Zieria gymnocarpa* regrew from sucker shoots emerging along the roots.

In contrast to *Z. gymnocarpa*, the other common shrub in Transect 73, *Acacia disparrima*, has remained fairly stable, with a minor drop between 2019 and 2022 (Figure 6).

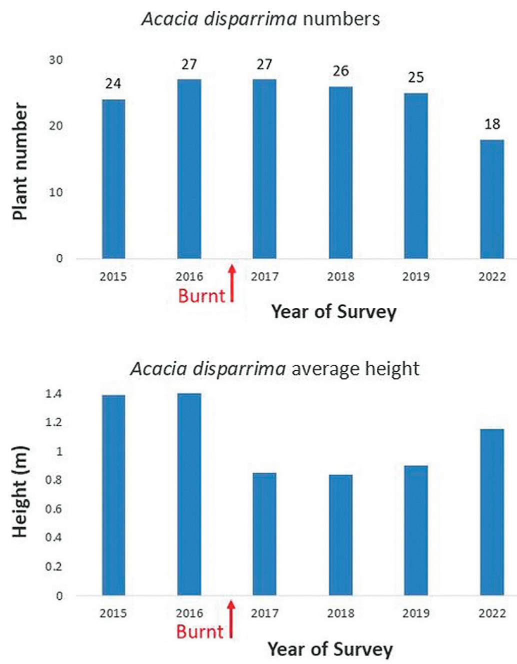

FIGURE 6. The number (top) and average height, ±1 standard error (bottom graph), of *Acacia disparrima* in Transect 73 at Belmont Hills, as a comparison with *Zieria gymnocarpa*.

Discussion

While these results are only based on three transects in one location of *N. lloydii*, and only one transect at the single known location of *Z. gymnocarpa*, they provide a snapshot of the dynamics of these two rare Brisbane bushland shrubs. The results confirm a previous observation by Halford (1998) that *N. lloydii* survives fire by vegetatively resprouting from the base of stems. We found 100% survival of burnt and unburnt plants, and rapid post-fire regrowth, indicating the sample population of *N. lloydii* at Changing Mountain appears to be stable and tolerant of low-intensity fire. However, no seedlings have been seen, and recruitment of *N. lloydii* may have been inhibited by a dense *Lantana montevidensis* ground layer in the area (Williams & Collins, 2022).

Based on the International Union for Conservation of Nature criteria (IUCN, 2022), the current status of Vulnerable at the state (NC Act) and Federal (EPBC Act) levels is supported for *N. lloydii*. That is, the species has a total extent of occurrence of between 5000 and 20,000 km^2, and has severely fragmented populations within the highly developed South East Queensland region. There is evidence of a decline in habitat quality on the basis of weed abundance, i.e. *Lantana montevidensis*.

In contrast to *N. lloydii*, the sample population of *Z. gymnocarpa* has undergone a significant decline in the last seven years. The relative stability of the associated *A. disparrima* indicates there is an issue selectively affecting *Z. gymnocarpa* rather than all woody plants in the area. It is particularly concerning because the species has such a limited known distribution (around 7 km^2).

The initial recorded drop in *Z. gymnocarpa* numbers occurred during a dry year when several *Zieria* plants were observed with dead leaves. It was independently noted that *Z. gymnocarpa* plants in an adjacent location also looked to be suffering from dry conditions and produced few fruit (G. Leiper, pers. comm., 17 May 2022). Multiple rare *Zieria* species in New South Wales have also dropped in number during droughts of recent decades (G. Wright, pers. comm., 12 May 2022). However, some of those species of *Zieria* have subsequently germinated massive numbers of seedlings (e.g. >1000 seedlings) after the high rainfall of recent years, including in sites burnt in the 2019 fires (Brown & Richards, 2022).

The lack of seedling recruitment by *Z. gymnocarpa* is unusual for a species of *Zieria*. Most *Zieria* species are fire-killed obligate seeders, a functional group that tends to produce more seedlings than do species that vegetatively regrow after fire, such as *Z. gymnocarpa*. For example, the Endangered obligate seeder *Z. bifida* of the Sunshine Coast hinterland recruited 188 seedlings from 19 pre-fire adult plants following a single fire (R. Thomas, pers. comm., 1 April 2015). *Zieria baeuerlenii* is another of the few species of *Zieria* that resprout after fire, which also shows population fluctuates linked to drought and has very limited, if any seedling recruitment (K. Coutts-McClelland, pers. comm., 27 May 2022). Therefore, the lack of seedling recruitment is not unusual for a resprouting shrub, especially one that can spread slightly via root suckers, and multiple *Zieria* species show strong fluctuations in population numbers, especially in dry years.

Using the IUCN criteria (IUCN, 2022), the current Queensland NC Act status of Critically Endangered is supported for *Z. gymnocarpa* and it is recommended it also be listed as Critically Endangered under the Federal EPBC Act. This is because the species has an extent of occurrence of approximately 7 km^2, which is at the lower end of <100 km^2. The Belmont Hills transect data presented in this paper show a significant population decline in the last decade (i.e. potentially an 86% decline within seven years). The population is fragmented by being split by the Gateway Motorway.

Further assessments will need t o be made to evaluate the population density of *Z. gymnocarpa* across its entire range at Belmont Hills and Mt Petrie. Small treatments, such as burning small patches in wet years, can be trialled with the aim of promoting plant numbers via well-spaced root suckers and/or seedlings. Germination and vegetative propagation trials and planting of resulting plants would be worthwhile.

The regional ecosystem in which these two rare shrubs grow (RE 12.11.5, eucalypt forest on metamorphic-derived soils on hills) is one of the most widespread across South East Queensland. These data highlight the variability of plant responses in this dominant vegetation type and the benefit vegetation monitoring makes to understanding population dynamics across the region.

In conclusion, monitoring of two rare shrubs of Brisbane eucalypt forests has found one species (*N. lloydii*) to be stable in the Changing Mountain (western Brisbane) area, including after low-intensity fire; while another, more restricted shrub (*Z. gymnocarpa*) to be declining in density in recent years.

These data highlight the absence of *N. lloydii* seedling recruitment, which may be linked to the abundance of the weed *Lantana montevidensis*, and also to rapid regrowth after fire and tolerance of at least occasional low-intensity burning. Further assessment of other *N. lloydii* populations, after a sequence of fires and after germination trials to assess seed dormancy, will increase our understanding of the dynamics of this species.

Additional assessment of the *Z. gymnocarpa* population is needed to understand the current number of plants in its only known population, as well as the role of burning, such as in moist conditions, in promoting further vegetative spread or seedling recruitment.

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A Rangelands Conundrum – the Division Within and Among Producers and Stakeholders Regarding Climate Change: Addressing the Challenge to Promote and Gain Consensus of Perception

David L. Lloyd OAM[1] and David A. George[2]

Abstract

The science of climate change is almost universally accepted by the science community, yet producers and other key stakeholders in the rangelands are divided in their beliefs and understandings of climate change and the part that climate change plays in extreme events that impact their businesses. To counteract that, this article suggests that emphasis on sound, educationally framed climate information will arm producers and stakeholders with leading-edge knowledge and techniques to meet the challenges of rapidly reducing their emissions and building resilience. They will require skills, knowledge, leadership and resources to adapt to a new reality. It is suggested that collaborative and innovative strategies are needed. Extension programs that are active, results-oriented and collaborative, such as those between multiple stakeholders, government and research institutes, are necessary. Inaction should not be justified through past mistakes, which must not be repeated. Authentic evaluation examining end-results and practice change are essential. This article identifies a series of strategies for future engagement with producers, and discusses resistance to change. Various methods for collecting support from producers and stakeholders are considered. It is concluded that incentives and the ways in which knowledge is transferred must be sufficiently robust so that political, industrial and/or ideological sabotage is resisted. This would represent an irreversible, changed approach to rangelands management, use and sustainment.

Keywords: climate change adaptation, risk management, belief systems, scepticism, action learning process

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Introduction

There is an underpinning need for all stakeholders in the rangelands to adopt best practices in adapting to a warming climate. The process chain for all products from our rangelands must continually evolve to remain competitive, relevant and sustainable in a rapidly changing world. Markets will demand low carbon product. Government and society are beginning to demand good corporate and industry citizenship, and land stewardship, and this is likely to intensify whilst nature does, and will, make conditions more challenging.

The science of climate change and its effects on the environment have been almost universally

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accepted by the scientific community (Anderegg et al., 2010). Local and global warming trends are supported by datasets locally, nationally and internationally (Bureau of Meteorology (BoM), 2018, 2019, 2020; Intergovernmental Panel on Climate Change (IPCC), 2021). The warming process is not part of a short-term cycle, but a trend that will prevail for the foreseeable future (Food and Agriculture Organization of the United Nations (FAO), 2013). Yet, there is a difference of opinion, a conundrum, with climate change sceptics and deniers influencing both the development of policy and many people in the community generally (Boycoff, 2013; Crowley, 2021; Mooney, 2005; Sattler, 2020).

A dichotomy of opinion on the significance of climate change was emphasised during the Rangelands Dialogue, a 2019 conference presented by The Royal Society of Queensland, at which only one paper specifically addressed that subject (Lloyd et al., 2020), among the 25 independent papers that were published (Sattler, 2020). A division of opinion was reinforced by subsequent email discussions in a monitored feedback process among participants (including pastoralists, scientists, economists and consultants). The feedback responses emphasised disagreement in both belief in climate change and the importance of addressing its implications for rangeland management.

The rangelands, expressly the extensive grazing systems of the semi-arid, low-rainfall grasslands and woodlands, and the savannah woodlands of northern Australia, are "stressed" (Hoban, 2020) and in poor and deteriorating condition (Briggs, 2020), with the natural resource base now further challenged by the effects of climate change. Extension aims to apply and accelerate adoption of best management practices in the rangelands, particularly pertaining to grazing management, pasture management and sustainable land use, in the face of climatic challenges. Notwithstanding the developments in climate science, the process to deliver education and extension, addressing such issues where confounding messages abound, is also gaining prominence (Bawden et al., 1984; Bawden, 2010). Can psychology help address this issue? Bawden et al. (1984) considered a systems approach most useful in enhancing problem solving and learning because it was superior to reductionist, discipline-based approaches. There are now more elegant methods for overcoming underlying psychological beliefs without manipulation (Ecker et al., 2022; Vraga & Bode, 2017; Vraga et al., 2020).

This article, a reference-based review, describes opposing beliefs of stakeholders in terms, on one hand, of the science itself and the practices needed to adapt to and mitigate climate change, and, on the other, of the views and influences of the sceptics (Maslin, 2019). It describes better processes that are being adopted and proposes focused techniques to apply to adult learning methodologies. These are needed to build capacity, to create positive informed debate, to influence attitudinal change and leadership, and to implement positive action (Davis, 2009; Hine et al., 2013; Knowles, 1975; Lloyd & George, 2008; Monroe, 2015; Reser et al., 2012). Although this article targets Australia's northern rangelands specifically as the catalyst in this discussion, the principles espoused are relevant in any other primary industry sector.

What Is the Fundamental Science Around Climate Change and What Are the Important Underpinning Elements?

A trending increase in temperature is caused by increasing greenhouse gas (GHG) [carbon dioxide, methane, nitrous oxide, ozone, water vapor] concentrations in the atmosphere, particularly during the past 150 years. The concentration of carbon dioxide, for example, ranged between 172 and 300 ppm up to the year 1750 (the conventional benchmark of the pre- and post-industrial era), to rise to more than 410 ppm by October 2020 (Arrhenius, 1896; Denning, 2021; Intergovernmental Panel on Climate Change (IPCC), 2001, 2013, 2014, 2021; National Aeronautics and Space Administration (NASA), 2021).

Throughout Australia, the average mean temperature between 2011 and 2020 was 0.77°C above the average, with a 0.9°C warming since the year 1970 (Bureau of Meteorology (BoM), 2018, 2019, 2020). In 2020 a national warming of 1.15°C above the annual mean temperature was recorded (Bureau of Meteorology (BoM), 2020). To emphasise the climatic extremes experienced during the past decade, 2019 was Australia's warmest year on record, with the national annual mean temperature 1.52°C above average and the mean maximum 2.09°C above average. It was also the driest year on record, with the nationally averaged rainfall 40% below average (277.6 mm) and much of Australia affected by drought (Bureau of Meteorology (BoM), 2020). This created widespread, extreme fire weather conditions.

Trending temperature increases cannot be dismissed as 'normally occurring' variability when there is a permanent move to a higher, most frequent value on the normal curve of 'average' temperature distribution. This provides clear evidence of the occurrence of a warming future (Figure 1). Since 1951, the warming recorded has had the effect of shifting the bell curve towards higher temperatures, and the higher 'extremes' happen more often (NASA, 2021, citing IPPC 2001 data). The warming measured will increase the probabilities of occurrence of extreme events that include both prolonged droughts and torrential rains (Thomas et al., 2007). This is the alarm bell for agriculture, as such extremes will decrease the reliability of production and threaten the yields of food, fibre, forestry, fisheries and pharmaceuticals (AgForce, 2017; Ag Institute Australia (AIA), 2018; Barlow et al., 2011, 2013; Luke & Macarthur, 1986; McKeon et al., 1988, 2004; National Farmers Federation (NFF), 2015; Queensland Government, 2013; Recher et al., 1990).

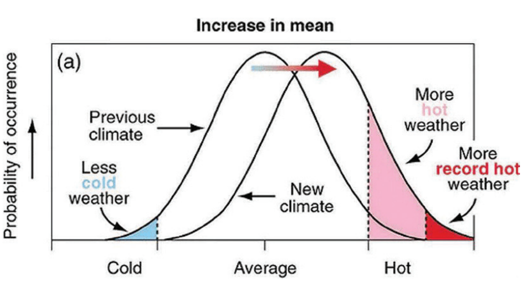

FIGURE 1. The changing schematic bell curve – from 'present' to 'future' of 'average' temperature – given a changing climate (Source: Data from Intergovernmental Panel on Climate Change (IPCC), 2001; modified from image reproduced by Naughten, 2012; accessed 2 June 2022).

Global changes in temperature and rainfall ascribed to 'climate change' are inexorably linked to the health of ecosystems, to sustainable agricultural productivity and to a secure food chain. In agricultural industries outside the rangelands, such extremes have had calamitous effects (for example, in the 2007–2008 southern hemisphere summer, there was a 98% failure of the Australian rice crop owing to the effects of low rainfall [drought] and low streamflow discharge). Rangelands are also susceptible to such climatically extreme events (Garnaut, 2008, 2011; Hacker & McDonald, 2021; Lloyd & George, 2008; McKeon et al., 1988, 2004; Stern, 2007; Stokes & Howden, 2010; World Commission on Environment and Development (WCED), 1987).

Climate change will initiate extreme events such as the sudden onset of direct and indirect climate disasters, and new vectors for human, plant and livestock pests and diseases. Such impacts occurring at 'local' level, particularly in the form of droughts and floods, cause severe hardship (Davis, 2009; Grains Research and Development Corporation (GRDC), 2009, 2015). The abilities of graziers to deal with different forms of risk, as well as changes to their frequency, severity and duration that exceed the historical experiences and risks associated with seasonal climate variability, will become ever more crucial and will demand a greater focus on education and implementation processes concerning climate and risk (Farmers for Climate Action, 2021; George et al., 2019; George, 2020; Hacker & McDonald, 2021).

What Are Relevant Adaptation and Mitigation Practices?

To address the influences of climate change on climate variability, the implementation of existing and more recently proposed, incremental and transformative adaptation measures is needed. These measures have been referred to as 'no regrets' and 'climate justified', respectively (George et al., 2019). Additionally, mitigation processes that reduce or capture GHGs to lessen the extent and severity of climate change and its effects must be applied and/or accelerated (Food and Agriculture Organization of the United Nations (FAO), 2013; Stokes & Howden, 2010).

Practices suited to managing both climate variability and climate change ('no regrets' actions) are practices that are already commonly used to manage our variable climate, and include (George et al., 2019):

- maximising pasture growth by best management practice;

- matching stocking rate to pasture growth using sustainable, risk-averse levels of pasture utilisation;
- building knowledge and skills to achieve best management practices;
- developing comprehensive plans for managing drought, flood, heatwave and fire risk;
- achieving sustainable and profitable land management that improves soil conservation, soil health, and water conservation and water use efficiencies through on-farm infrastructure and good soil management practices;
- monitoring and ensuring water quality and quantity;
- providing animal health feed supplements;
- establishing or improving shelter/shade-belts and considering agro-forestry/soil carbon capture; and
- evaluating and implementing income options for increased on-farm carbon sequestration and energy production (including diversified and new technological alternative actions such as embracing solar and wind energy generation).

Practices proposed for managing the increased risks from climate change ('climate justified' actions) are implemented as incremental and transformative measures for better managing climate change, and could include (George et al., 2019):

- selecting livestock with greater thermoregulatory control and tolerance to heat stress;
- developing and using crop and pasture cultivars with greater heat, pest and disease tolerances, and that are better suited to projected temperature and rainfall changes;
- livestock management methodologies that help mitigate GHG emissions;
- assessing the effects of climate change risks ('likelihood' multiplied by 'impact') as part of risk management processes;
- further developing and evaluating best management practices to manage the complexities and uncertainties of climate change;
- increasing safety margins on flood-prone structures and establishing animal refuges to cater for more extreme rainfall events;
- increasing property and business diversification and planning that manages for extreme weather events;
- considering the costs and benefits of increasing security on water supplies;
- increasing investment in emergency services such as fire-fighting facilities and capacity to respond to increasing bushfire risk;
- diversifying a portfolio of income, including carbon farming; and
- assessing how and when to implement transformational change or planned 'retreat'.

Many of these practices are not new (Food and Agriculture Organization of the United Nations (FAO), 2013; Stokes & Howden, 2010), yet, notwithstanding some level of ongoing extension, adoption has been generally disappointing (Briggs, 2020; George et al., 2019; Hoban, 2020; McKeon et al., 2004). Other factors, too, have been responsible for a less-than-widespread uptake. For example, where income is relatively low and the cost of adopting and implementing expensive risk management measures is high and incentives are not provided, positive action is difficult (Anon., 2011). Furthermore, climate change adaptation practices are complex, and unique to individual operations and enterprises. A single strategy response is likely to fail because achieving adaptation goals requires the adoption of multiple strategies (George et al., 2019; Randall et al., 2012). Comprehensive planning for climate change at the farm level is required (George et al., 2007a,b,c).

What Is the Place for Risk Management and Best Management Practices?

Risk management is the systematic application of management policies, procedures and practices to identify, analyse, assess, treat and monitor risks (ISO 14091, 2021). It incorporates choosing appropriate options to manage risks that are concomitantly encountered around climate, production and farm finances. Enhanced risks that are associated with climate change in the rangelands are associated with increased temperature and the extremes encountered with changes in the quantity, distribution and variability of rainfall. These create ecosystem hazards including heatwaves, droughts, reduced water security, bushfires and floods (McKeon et al., 2004), as have been described previously.

There are well-established protocols for prioritising risk management impacts in adapting to climate change. Commonly applied risk management practices have been inadequate in managing drought generally because of the apparent combination of:

(i) the drought's severity, extent and duration; and
(ii) the inability of previously successful actions and adaptations that failed when experiencing extremes – impacts that are now being associated with climate change (Hacker & McDonald, 2021; Sattler, 2020).

Both the application of the precautionary principle and education underpin and enhance risk management practice (George et al., 2019; George, 2020; Lloyd et al., 2020).

Why Should the Precautionary Principle Be Considered and Used?

The precautionary principle is a process for moving forward in the face of uncertainty and reducing the risk of rationally determined, adverse effects (Intergovernmental Panel on Climate Change (IPCC), 2021; World Commission on Environment and Development (WCED), 1987). While the science of climate change is clear, climate change projections remain uncertain because GHG emissions drive the change and are still increasing. This is because the amounts and types of GHG being emitted and mitigated globally are a result of policy decisions that are evolving (Intergovernmental Panel on Climate Change (IPCC), 2021). Future projections are thereby imprecise. Therefore, it is necessary to extrapolate the 'range' of 'optimistic' and 'pessimistic' future scenarios using scientific knowledge, due diligence and the (as yet) uncertain global responses. When an activity genuinely threatens harm to humans and ecosystems, precautionary measures should be taken, regardless of the effects not being fully understood. For this reason, *inter alia*, scientists are conducting research to limit increases in GHGs and to capture carbon (Dunstan, 2020; Meat and Livestock Australia (MLA), 2020).

Precautionary actions, when applied in the rangelands, should minimise and delay the impacts of climate change. Rangeland managers would then have a greater role in ensuring future food security, both locally and globally, by adopting practices that enable better adaptation to climate change, and by capturing carbon. Assistance in the form of financial incentives, support and coordination as a new Carbon Economy – an economy driven by the imperative to limit carbon emissions – evolves (Lloyd & George, 2008) would help build capacity and accelerate best management practices.

How Can Applied Climate Education Address Such Complex Issues?

The science of climate change is well established and has been well explained during the past three to four decades (Intergovernmental Panel on Climate Change (IPCC), 2021; McKeon et al., 1988; Paxton, 2021). There is a strong basis, then, for assisting rangeland producers in implementing both established and new options across all components of their businesses and their business management (Bode et al., 2020). Since each property is unique, plans for individual properties and circumstances need to be tailored to those specific characteristics (Monroe et al., 2017). Applied education has been used to achieve this (Clewett et al., 2011; Clewett, 2012; George et al., 2005, 2007a,b,c, 2009, 2016, 2019; Knowles, 1975). Accelerated processes to upscale management change are essential, not optional (Megalos et al., 2016) as the impacts of climate change are happening already.

What Is the Anti-science Message Around Climate Change, and What Are the Main Arguments of the Sceptics and Deniers?

However, alternative views do exist. Despite science identifying and describing the effects of climate change and developing policies to mitigate against or adapt to them, an opposite view has been taken by many direct stakeholders and powerful voices in the Australian community (Burke, 2019; Gurney, 2021; Kennedy, 2019; Maiden, 2019; Mooney, 2005; SBS News, 2021).

For example, since 2007[a] the science surrounding anthropogenic-induced climate change has become highly politicised, central to which has

[a] The year 2007 is chosen only to highlight these issues – the level of politicisation that has occurred concerning climate change prior and post this time is subjective, with our reference list indicating key timelines of thought.

been a concerted, noisy media campaign from sceptics[b] and deniers. They have not only opposed the scientific basis of climate change but have been strongly driven by perceived negative economic implications. In addition, prominent politicians have labelled the climate change debate as a "distraction" (SBS News, 2021) and stated that "the idea Australia can stop climate change is 'barking mad,' and global warming is a better problem than the next ice age" (Maiden, 2019), and that "God is the solution to climate change" (Burke, 2019). The sociological impact of these views is to reinforce such values and opinions in the minds of the sceptics (Monroe et al., 2015).

Arguments used by climate change deniers and sceptics may be generally aggregated into:

1. The use of 'short-term' data in a 'longer-term' world in which climate has always been changing is questionable (thus promoting the view that current global warming is simply part of a 'natural cycle').
2. Overstated impacts are projected and promoted by scientists to meet their own ends.
3. Economic issues that question the relative significance of a particular sector (Maslin, 2019).

Even when considering these singularly or collectively, those in positions of influence, including government and industry, were (at the time of the Rangelands Dialogue) doing nothing differently than supporting standard extension and allied processes, and deeming them sufficient (George, 2020; Hacker & McDonald, 2021).

Questionable Data

Data that are deemed 'questionable', based on the relatively 'short' duration of their collection, lead to a conclusion that the records on which climate projections are based are inadequate, and that climate change cannot be conclusively accepted and therefore should be rejected (Boycoff, 2013; Crowley, 2021; Maslin, 2019). This accepts that whatever climate extremes prevail, they are part of the 'normal cycle' and that scientists use 'alarmism' to gain investment for climate change projects (Crowley, 2021). This is accompanied by a belief that new and yet-to-be introduced 'on-farm' technologies *per se* (and not including climate risk management practices) will overcome the variabilities in a perceived 'normal cycle' of climate. Associated with this is a failure to recognise the lag time between the onset of the change itself, the observation of the effects of change, and the time needed to develop new technologies. For example, to genetically improve plants and animals, cycles are measured in years. This is likely to impact on and increase the effects of reduced capital returns to producers at times when stock numbers are rebuilt after drought. Ecosystem function data on which production from rangelands rely, e.g. grass growth, grass recruitment episodes and the occurrence of pests, weeds and diseases, seem also to be ignored. Those economists who proclaim the unreliability of climate data while taking an anti-climate change view seem at ease in relying on their own economic data to support their claims that technology will overcome such problems (Maslin, 2019; McCright & Dunlap, 2011; Oreskes & Stern, 2019).

Overstated Impacts

As a result, the scientific impacts of the supposedly 'questionable' climate data are considered to be overstated – a compounding effect. Thus, the deniers and sceptics see no need to adjust long-standing management responses and no need to change risk-management priorities. The climatic extremes are simply a part of the 'normal cycle', which perpetuates the implementation of current 'reactive' responses. Therefore, potential 'proactive' approaches in which incremental and transformational adaptive or mitigation measures should be applied are deemed 'politically' unnecessary (Burke, 2019; Hare, 2021; Martin, 2021).

Relative Insignificance

The agricultural/rangeland sector within the wide range of primary production industries is regarded

[b] Note, however, that an analysis of such arguments presented regularly by one journalist has shown them to be inconsistent with genuine scientific scepticism and to be largely ideologically driven (Gurney, 2017). Another high-profile journalist has consistently denied the link between the severity of drought, heatwaves, bushfires and water shortages to climate change, claiming that climate change is "a hoax", and "there's no evidence whatsoever to support [it]" (Kennedy, 2019).

as relatively insignificant by some economists, including Myron Ebell, Pat Michaels, Fred Singer and Sallie Baliunas (Boycoff, 2013; Crowley, 2021). Others take an opposite view (Garnaut, 2008, 2011; Stern, 2007). The former group tends to dismiss the allocation of funding to combat climate change as being of limited economic significance, which implicitly fails to accept the existence and impacts of climate change – thereby supporting a 'denialist' notion (Gurney, 2021; Kennedy, 2019; Maslin, 2019). The latter groups regard climate change action as imperative.

Despite this, the deemed insignificance of the economic value of the Queensland rangelands is arguably based on an incorrect premise. The Queensland rangelands carry about 63% of the state's cattle herd of approximately 10.6 million head, a best estimate based on livestock numbers from Meat and Livestock Australia data for 2017 (Beef Central, 2017), or about 29% of the national cattle herd, thereby contributing about AU$3.8 billion to Queensland's economy through cattle products alone (Lloyd, 2021). Sheep and goat products are produced almost exclusively in the rangelands, but their contribution is lower compared to that of beef.

How Is It Possible to Overcome Such a Dichotomy of Beliefs and What Would Be the Benefits of Doing So?

Since the decline of government-funded Research, Development and Extension (RD&E), services, e.g. in Queensland from 5% of the value of the proportion of agricultural gross value of production in the late 1970s to just over 3% in 2007 (Queensland Government, 2013), a decreasing role of publicly funded strategic extension has limited the focus on best practice management for the emerging risks of climate change. Needs to address climate change were identified by Barlow et al. (2011, 2013) and, to some extent, the challenges were recognised by the Rural Industry Research and Development Corporations (RIRDCs), the Grains Research and Development Corporation (GRDC, 2009, 2015) and industry (National Farmers Federation (NFF), 2015; AgForce, 2017). However, while there was an increase in implied action such as the breeding of better-adapted crop plants, there was a relative absence of direct 'on-ground' management and an unwillingness to begin a process of perception change – so creating the necessity to convene the Rangelands Dialogue (Sattler, 2020).

Nevertheless, in 2021 there were signs of change (Rolfe et al., 2021). Farmers for Climate Action is a group of more than 6000 independent, non-politically aligned Australian farmers. Using science-based information, they are beginning to empower farmers, collectively, to take a lead on climate change action, particularly by putting significant pressure on government.

At the same time, RIRDCs are now investing in direct action to mitigate and adapt to the effects of climate change. For example, Meat and Livestock Australia (MLA) (2020) has initiated an ambitious, direct investment program 'Becoming Carbon Neutral by 2030' (the 'CN30' program) which, in conjunction with industry partners, government and research providers, is aiming to mitigate the emission of greenhouse gases by the livestock industries and adapt to the effects of climate change. This is planned through nine major research, development and adoption activities. These include:

- improving animal genetics, husbandry and nutrition to meet changed circumstances;
- reducing methane emissions from livestock;
- enhancing soil carbon sequestration and sequestration measurement processes;
- identifying further the role of dung beetles;
- studying the effects of new pastures, legumes and shrubs on lowering methane emissions; and
- developing renewable energy technologies in various ways.

The collaborative association of all stakeholders, from the conceptualisation of projects to the adoption processes employed, will determine the success of the program's vision.

Away from the rangelands, GRDC (Dunstan, 2020) is investing initially in a partnership with the Commonwealth Scientific and Industrial Research Organisation (CSIRO) to gather baseline information around the levels of emission from the grains industries, to prioritise and develop a plan for emissions reduction. This is designed to provide stakeholders, nationally and internationally, with an optimistic, data-based pathway to understanding the baseline for future investment around climate change – a pathway that includes identifying best management practices. This is also proposed to result in the development of a Grains Industry Sustainability Framework which would be led by grain grower organisations.

These considerable initiatives, *per se*, are likely to act as catalysts to a better understanding by producers of the science of climate change and its impacts on farm management and the research projects that are setting out to minimise those impacts. The CN30 initiative by MLA focuses particularly on the adoption of research outcomes by doubling prior investment in adoption practices. All projects within the CN30 initiative are using collaborative processes throughout, by creating partnerships between producers and all stakeholders (MLA, industry bodies, consultants, scientists, service providers and other agencies), supported by appropriate education and extension services and practices.

Adult learning education and extension processes, as proposed in the CN30 initiative and by other agencies and operatives, should provide a strong foundation to enhance a social osmosis of the adoption of climate change mitigation and adaptation measures, as well as an understanding of the science of climate change and its effects (see companion papers George et al., 2005, 2007a,b,c, 2009, 2010, 2011, 2016, 2019). These processes provide a platform for needs-based adult learning, untarnished by individualistic philosophy. Historically, extension services have been focused on technology transfer to increase production, sustain the natural resource and train farmers – the 'do it this way' approach. The adult education extension process proposed is not new, but refinements to implement a 'better' process will be proposed. It differs from the traditional technology transfer methodologies through facilitating the formation of farmer groups to deal collectively with issues relevant to the participants. The extension process should include learning about off-farm issues through partnering in the process with key off-farm stakeholders (George et al., 2019). Modern extension is thus the collective provision of 'applied' knowledge and skills by all organisations and personnel supporting all engaged in agricultural and pastoral production along the value chain, particularly producers (Davis, 2009).

What Are Some Fundamental Successful Principles and Approaches to Climate Change Already Being Used in Australia and Other Parts of the World That Could Effectively Be Applied to the Rangelands Now?

Will current strategic extension processes focused on climate change and based on adult learning, such as within the CN30 initiative, be enough to enable deniers and sceptics to learn that climate change is real, and that its effects are immediate? Will this be adequate to address the dichotomy of opinion and change perceptions? The impetus gained through collaborative direct action now being initiated, e.g. through the CN30 initiative, should help create a direct focus on solutions to the effects of climate change. However, to create a more substantial belief in the science of climate change among pastoralists and producers in all other agricultural sectors, subtle processes – more subtle than are currently applied – will need to be adopted. Climate change 'evangelism', the 'believe me' approach adopted historically, is ill-advised and insufficient, and the various views that exist currently demonstrate that this simply does not work. More sensitive principles – principles that have not been effectively applied – need to be embedded within the adult learning extension process (George et al., 2019) and are broadly outlined below.

People are selective in what they choose and want to believe. Attitudes are formed by personal experiences and from trusted sources and individuals (Monroe et al., 2017). The climate change deniers and sceptics set their attitudes by believing in sources that they trust and that reinforce their beliefs. To ameliorate that and to enable change, a new and different trust must therefore be gained via appropriately facilitated processes. That will not occur quickly; it will require patience and skill, together with a progressive, consistent presentation of those processes needed to gain trust and approval. Highlighting already successful leaders is a good start. Analysing their 'how-to' is an example that presents principles worthy of emulation. Thus, the challenges in delivering an effective, unifying extension program around climate change to an audience of producers and stakeholders who have an array of existing beliefs about the science itself can be defined through four lenses (Bode et al., 2020):

1. *Climate change is complex, uncertain, and variable*. When confirming the scientific belief that climate change is real, the use of global and local warming data, together with easily relatable analogies around the occurrence of extremes, is recommended.
2. *People learn and remember selectively*. Be patient, provide time to record the observations of participants regarding their experiences of climate-based extremes, gain trust by avoiding a 'for and against' debate, initiate small group debate (stories and scenarios) that link the known to the unknown, and use a timeline to list a changing frequency of climate-based extremes.
3. *People pay attention to those who are like them*. Cultural settings need to be allowed for when planning and executing effective personal communications (Bode et al., 2020). Two groups these researchers commonly found in extension audiences when dealing with climate change were those that could be clumped into 'individualistic' and 'egalitarian' cohorts. The former favoured business ('market-driven') solutions, while the latter leaned more towards government action. The reasoning behind these different approaches was that one group thought the competitive arena leads to fairer outcomes (Kahan, 2010), while the other believed a governmental approach is more equitable. The main takeaway message we consider from these findings is to know your audience and their needs and provide specific information to satisfy both groups (George et al., 2016). Furthermore, the role of the extension process is to convey reality to an audience comprised of progressives and those who are more conservative. The process is a delicate balance, framing issues in a way that speaks to the values of the broad spectrum of participants, avoiding framing climate change messages around fear, but providing examples of local solutions to gain trust and relevance.
4. *Audiences vary and issues need to be simplified*. To reiterate, rangeland manager audiences possess wide-ranging beliefs and values around climate change and climate change management. Better audience trust and attention are likely to be gained through specific use of simple agricultural examples that endorse best management practices and climate change risk management.

Therefore, evaluation of standalone and synthesised programs and projects (and the integration of authentic feedback into programs) should be integral to and help create a successful pathway that progresses adaptation and mitigation of climate change into the future (George et al., 2019). Nevertheless, we emphasise again that the process of delivery is vital to gain better acceptance and adoption of measures to adapt to climate change. A certain way to provoke people to ignore the climate change issue is to frame it within fear-based messages; however, presenting clear solutions helps to overcome this challenge (Center for Research on Environmental Decisions, 2009). People across all spectrums feel hopeless and helpless when given, without effective solutions, sensationalist messages on how climate change will reshape society as we know it. Extension processes must steer away from highlighting the potential for disaster, providing instead examples of local solutions and the benefits of adapting to and mitigating the extreme effects of climate change.

Conclusion

The difference in opinion between those graziers and stakeholders who comprehend the reality of climate change and its impacts and urgency, and those who continue to deny and be sceptical, has frustrated rational extension process and related dialogue, particularly during the 21st century when the urgency to mitigate against and adapt to climate change has become evident. Extension processes in the northern rangelands of Australia have not been adequately successful, over a period of decades, in delivering research outcomes that have enabled a sustainable improvement to the condition of the natural resource, a condition that has trended downwards during periods of severe drought. Thus, we propose that the implementation of truly collaborative direct action, e.g. that of the MLA, together with an understanding and application of subtle adult learning extension processes that set out to gain trust during that process, will lessen the gap between acceptance and denial of climate change and its impacts within the farming communities.

This provides an opportunity for a new approach, an approach that combines collaboration between all stakeholders, but particularly the graziers, and a more subtly focused action learning process. It is a great challenge that will involve new and existing skills around all facets of property, livestock and natural resource management, including issues beyond the farm gate, and extension processes that are finely adjusted to maximise the gaining of trust. Especially tailored extension can be successful if delivered in an authentic, trustful, respectful and non-threatening manner.

Companion papers (as mentioned previously and listed in our references) elaborate on more detailed specifics of the 'how-to' of effective climate change risk management and education principles. Such action is both urgent and important if timely actions are to be applied on ground. Accelerating the rollout of better-qualified facilitators and educational courseware designed to address the impacts/options (adaptation and mitigation) of climate change in rangeland management is essential, not optional, and if applied and accelerated in rollout, will translate into improved socio-economic and environmental benefits. It is recommended that any educational courseware should encompass on-farm plans that build capacity by way of the broad competencies: (1) surveying climate and enterprise data; (2) analysing climate risk; and (3) developing climate risk management strategies that align with industry best practice.

These embed within them the principles espoused previously: of respectful dialogue, and peer discussion that builds, not divides. Utilising local 'how-to' case studies that show how successful businesses, governments, individuals and communities have reduced their energy consumption or greenhouse gas emissions, or how they are implementing climate adaptation plans, will better enable success. This alone, however, is not enough. To reiterate Kahan (2010), educationalists need to learn and apply how to best present information in forms that are agreeable to culturally diverse groups, and how to structure debate so that it avoids cultural polarisation. As such, policy making has to be backed by the best science and a theory of risk communication that integrates culture in decision making.

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Coal Seam Gas Mining: An Assault on Farming Land, Water Resources and Property Rights

Peter Dart[1], Colin Lynam[2], Revel Pointon[3] and Geoff Edwards[4]

Abstract

Coal seam gas mining in the Surat and Bowen Basins in Queensland, Australia, has developed rapidly over the past decade. Many landholders are concerned about the effects of the industry on groundwater and agricultural resources and the weakness of official oversight, recently criticised by the Queensland Audit Office. Gas and water extraction is now extending under some of the most productive agricultural lands in Australia, the Darling Downs. Uncertainties remain as to the impacts of gas activities on aquifers. The water extracted along with the gas is often salty, and the method of disposing of the salts is a contentious, unresolved issue. The power imbalance between industry and landholders and weak regulation of industry hinders efforts by the industry to obtain a social licence. Governments have, to a large extent, neglected the region-wide and long-term effects of the mining. Extracting gas and water from the coal seams leaves depressurised zones, which lead to subsidence of the earth layers above the seam and leakage of aquifers into the coal seams with deleterious consequences for agricultural production. The statutory 'make good' process for compensating for loss of the aquifer water does not adequately offset the negative effects on the hydrological resources and on agricultural production. The prevailing self-regulation, lack of baseline assessment and inadequate monitoring of the mining processes are abrogations of government responsibility and the precautionary principle. As the industry is still ramping up, there is precious little time to protect agricultural land and the natural systems that underpin agriculture from potentially irrevocable damage.

Keywords: groundwater, subsidence, aquifer, salt, agriculture production, regulation

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Introduction

The current era of extraction of coal seam gas (CSG) began with exploration wells in mid-western Queensland, Australia, in the late 1970s (Miyazaki, 2005). Since then, a wide range of both demonstrable and potential adverse consequences have been brought to scholarly and public attention. Prominent among these has been the inability of landholders to prevent incursions upon their properties by drilling rigs and extraction infrastructure, an impotence long embedded in the statutes that govern the industry. Other biophysical and socio-economic issues such as inadequate environmental assessment and baseline monitoring, depletion and contamination of

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groundwater resources, land surface subsidence, deposition of tonnages of saline wastewater, fugitive emissions of methane, boom-bust effects on employment and rents in the service towns and health effects (Haswell & Bethmont, 2016) have featured in public commentary and submissions to official inquiries.

The industry has not yet been able to negotiate an inclusive social licence to operate among the farming community, although sentiment has moved marginally towards acceptance among the townspeople (e.g. Walton & McRea, 2018; Luke & Emmanouil, 2019). This has come about particularly due to major disquiet about procedural justice, the imbalance of power between the communities affected and the industry, inequitable distribution of risks, limited assessment and oversight of the industry's activities by governments, the short-term nature of the mining set against the long-term disruption to communities and farming, and neglect of regional implications and intergenerational equity. A major community concern is the disparity in water extraction rights between the landholders who are constrained by statute and the CSG companies who enjoy practically unlimited rights to extract.

There are many accounts of the history of this industry and its current status (e.g. Towler et al., 2016; OGIA, 2019b). Concerns about demonstrable and potential effects have prompted a range of responses. For example, landholders and environmentalists collaborated to establish the Lock the Gate Alliance, a protest group of civil society raising concerns around the expansion of CSG and coal mining. The Australian Senate established a committee of inquiry into the management of the Murray Darling Basin (Parliament of Australia, 2013) with 381 submissions, which noted the broadly based opposition to the industry and recommended that landholders should be given more rights to reject company proposals. A further Select Committee on Unconventional Gas Mining established in November 2015 received 318 submissions and produced an Interim Report (Parliament of Australia, 2016) highlighting concerns about the health, social, business, agricultural and environmental impacts of the industry prior to the Committee's dissolution due to the election in July 2016. Four gas companies joined the Commonwealth Scientific and Industrial Research Organisation (CSIRO) to establish the Gas Industry Social and Environmental Research Alliance (GISERA; also see Glossary in online Supplementary Material), with majority funding from governments.

Federally, a 'water trigger' was established in the *Environment Protection and Biodiversity Conservation Act 1999* (Cth) (EPBC Act) in 2013 which made water resources in relation to CSG and large coal mines a matter of national environmental significance, requiring assessment. The Queensland Government's oversight has been analysed by the recent Queensland Audit Office (2020) Report #12, *Managing Coal Seam Gas Activities*. This report specifically critiqued the assessment process under the *Regional Planning Interests Act 2014* (Qld) (RPI Act) and the need to better ensure that stakeholders' concerns are adequately taken into account, especially in regard to risk-based planning, compliance management and database management, and information sharing across agencies.

These measures, which aim to understand more about the effects of CSG extraction and/or to ameliorate any adverse effects, operate however in the shadow of unambiguously extensive pressure by fossil fuel industries and governments to unlock ever greater quantities of this underground natural resource. An example was the public call in 2021 by the head of the Australian Competition and Consumer Commission (ACCC, 2021) for changes in the way the industry operates to meet the potential crisis in gas supply to the eastern seaboard. Gas markets were not working to keep prices low, as imperatives for the gas companies were to fill contracts written in more optimistic days to export gas from Gladstone. This prompted the Australian Government to institute the Australian Domestic Gas Security Mechanism, which aims to maintain domestic natural gas supply (see Note 1 in Supplementary Material). The saga hints at pressure on the companies to produce more gas from their fields.

This paper has been prompted by anecdotal reports from the Darling Downs (see Note 2 in Supplementary Material), a geographical area of fertile, arable soils west of the regional city of Toowoomba, that CSG regulation and policy are not preventing serious and possibly irreversible damage to the productive potential of the district's natural agricultural resources. Lacking access to proprietary information held by the gas companies and the financial and technical resources to conduct independent investigations, the authors are basing the paper on first principles of gas drilling, well construction, hydraulic fracturing and statutory accountability, supplemented by anecdotal reports of damage.

At the heart of this paper is a twin concern: first, that there is a glaring disconnect between what is happening on the ground and the aspirations of a statutory framework that assumes any adverse effects are being satisfactorily managed by conditions; and second, that there is no adequately funded body sufficiently empowered and independent of commercial or political influence to confirm the validity of the opposition to this industry expressed by numerous landholders, First Nations, scientists and environmentalists.

The paper first examines the operational issues – disruption to farming, management of produced water, effects of depressurising coal seams on other aquifers, and potential for connectivity and subsidence. It then outlines issues around the disquiet in the community about the regulatory regimes under which CSG mining is allowed to operate, demonstrated through landholder responses, a Queensland Audit Office review, regulation philosophy and industry impacts on property. The Conclusion summarises these findings and the portents for future coexistence of agriculture and CSG mining. The historical background to the current CSG industry operation in the Surat and Bowen Basins, parts of the Great Artesian Basin and major agricultural production areas in Queensland is given in the Supplementary Material (Section 3).

Aboriginal People and Groundwater

First Nations' interests in the health of their Country, which has in many parts been widely affected by gas activities, are less recognised and protected in law than even agricultural practices. Moggridge (2021, p. 15) documents "many stories that indicate the linkages between surface water, groundwater, lakes and rivers, cave systems, natural springs, thermal springs, rain events recharging the aquifers". These stories record a precise classification system for sites within First Nations' Country, upon which their survival depends. While an adequate treatment of First Nations' interest in gas extraction and disruption of the land profile is beyond the scope of this paper, all stakeholders are urged to access First Nations' insights into the interconnectedness of resources that contemporary science treats separately, in order to enrich public debate and official policy about the industry. The law requires this: section 28(2) of the *Human Rights Act 2019* (Qld) specially protects the rights of Aboriginal and Torres Strait Islanders, which must be upheld in all government decisions. An investigation of the adequacy of regulations to respect First Nations' interests in protecting their Country is overripe for further research, as recommended by Trigger et al. (2014).

The Issues

Landholder Rights

Unlike the major portion of Queensland's inland pastoral country (which is predominantly leasehold; see Note 3 in Supplementary Material), most of the Darling Downs arable lands are freehold. Owners of freehold land enjoy broad powers to choose whether to develop their land and are entitled to peaceable possession and to eject trespassers. These rights are grounded in common law, which evolved to protect landholders from unjust intervention by mediæval governments (Edwards, 2006a; Vanderduys & Edwards, 2004).

However, ownership of 'minerals' and 'coal and gas' is normally not included in freehold and leasehold titles in Australia, and in Queensland these resources are allocated by two separate regimes of tenure administration. The separation of resource tenure from land tenure is partly a consequence of the opportunistic nature of discovery of deposits of resources, but at its core is a tool for securing the public interest, to allow the state to capture royalties and to manage the potentially deleterious side effects at a scale that would defeat individual landholders. However, these beneficial outcomes require the state to avoid regulatory capture by the companies and also to defend the property rights of landholders, which itself is a matter of public interest.

From the separation of Queensland as a colony (1859) (and even before then – see Christensen et al., 2008), the legal doctrine of Crown prerogative was used to reserve minerals to the Crown out of many or most grants of land, but the practice was not universal and many early titles conveyed coal to the owner. These rights, which exempt the owner from paying royalties and so are immensely valuable to modern coal miners, were preserved by section 21A of the *Mining on Private Land Acts, 1909 to 1965*. However, the *Mining on Private Land Act 1909* reserved "minerals" to the Crown in all subsequent land grants. The 1909 exclusion has been extended to include unconventional gas (shale or CSG) by statute (see Note 4 in Supplementary Material).

The extraction of coal seam gas is administered under the statutory regime for allocating oil and gas (*Petroleum and Gas (Production and Safety) Act 2004* (Qld)) (P&G Act). Under the Act, the state allocates rights as: first, a licence to prospect; and then, via, for example, a petroleum lease, the right to produce gas. For gas, this right comes also with a duty to manage the associated produced water as a regulated waste under the *Water Act 2000* (Qld). This enables the applicant company to enter into an agreement with the landholder to gain access to the underground resource and to the land to establish access roads, a pad to drill the gas wells, and the gathering lines to take the gas and water away to treatment plants. The landholder's right to exclusive possession of the land is compromised (Taylor & Hunter, 2019).

Typically, the CSG company is required to negotiate a Conduct and Compensation Agreement (CCA) with the landholder, to compensate for the effect of the CSG activities on farming activity. The CCA sets out the arrangements for activities to be undertaken on their land and also any agreed compensation to 'make good' damage likely to be caused by the CSG operations. The management of impacts is typically addressed under an adaptive management approach explained in more detail in the Precautionary Principle section of this paper.

Various gas companies are now drilling under farms from neighbouring properties, thus affecting the land used by the farmer without establishing ground structures on the under-drilled farm. There are anecdotal reports of at least 48 wells of this kind. To date, companies have not considered that drilling under land would trigger the rights of the landholder to enter a CCA or to negotiate 'make good' arrangements. This interpretation is subjective and arguable, given the significance of the activity and its potential consequences. The inability to enter a CCA leaves landholders with under-drilling at a distinct disadvantage, particularly as it impedes the ability to ensure that there are baseline assessments of groundwater resources or land levels. Without baseline assessments, it is exceedingly difficult for a landholder to then demonstrate that the drilling has been the cause of any effects on their land after the fact and to obtain compensation or seek enforcement against an operator. Arrow Energy was fined in March 2022 for not even notifying landholders that the company was undertaking directional drilling under land (Queensland Government, 2022), as a result of an investigation by the government after many landholder complaints into the legality of the activity.

Companies usually require that individual CCAs with their 'make good' arrangements not be made public. This reflects a huge imbalance of power between the mining company and the affected landholder, who has no simple options for redress and is denied the knowledge essential for collective action with neighbours. The negotiation process can be contentious, expedient and inequitable (see also Taylor & Hunter, 2019).

Alarmingly, more than 233 historic landholders' water bores have already been depressurised to less than the trigger level where 'make good' compensation is required under the *Water Act 2000*, as outlined by the GasFields Commission (GFCQ, 2022a) and as described on the Business Queensland website (Business Queensland, 2020, 2022). More than 700 more bores are predicted to be affected to a level requiring 'make good' (OGIA, 2022). Further, while there are 'make good' arrangements for loss of groundwater in bores under the *Water Act 2000*, there is currently no 'make good' framework for subsidence.

In summary, the Queensland Government has allowed directional drilling under land for which there is typically no agreement with the landholder about access or compensation for damage, nor sufficient baseline assessment to properly remedy any effects. The GFCG has negotiated a Landholder Indemnity Clause for use in new CCAs which they believe obviates the issue, but its validity has not yet been tested (GFCQ, 2022a,b). At issue, however, is the lost value of the natural capital when land subsidence is caused over a large scale and aquifers are drained, not to mention loss of annual productivity and destruction of First Nations' interests. In addition, an unfair onus is on the landholder to prove that any impacts, including subsidence, are the result of the gas activities, which is impossible if no baseline assessments were undertaken.

Legislation sets the stage for conflict between incoming holders of gas tenure and the holders of tenure over the land surface. Legislation is not preventing damage to the land surface or landowners' assets and does not give landholders the right to refuse access.

An informal insight into the Queensland Government's dismissive approach to landholders' concerns was given by Acting Director-General, Department of Resources, Mike Kaiser, during a panel discussion of the Community Leaders' Council on 10 June 2021 (GFCQ, 2021a): "… these are deeply emotive issues" that will not be resolved solely by science and evidence, which is not wrong, but misleading, because emotive responses are generated on account of real-life transgressions. Kaiser continued (GFCQ, 2021a): "Regulation can tell a company what it can do and can't do, but it can't tell a company what it *should* do … considering 'should do', you start getting into ethics and moral considerations, and trust …". Yes, the companies *should* work harder to earn the community's trust, but the statement seems to absolve the Department as simply 'regulator' (a minimalist description of its role) from responsibility for protecting the public interest and for creating a trustworthy regime for the industry, using a range of tools including tenure allocation, regulation *sensu stricto*, policy, public administration, taxation and suasion ('jawboning'). The Council's theme of "Cultivating Coexistence – learning from experiences, facing challenges and harnessing future opportunities" (GFCQ, 2021a) is also telling, as it seems implicitly not to envisage the prospect of refusal of applications for CSG development.

CSG Drilling and Disruption of Farming Activities

Directional or deviated well drilling along a coal seam is an advancement in the drilling process in the Surat Basin recently introduced from the USA, where about 17% of oil and gas wells are now 'horizontal' (EIA, 2022). For the Surat Basin Cumulative Management Area, Arrow/Shell outlines how this would minimise the surface area required for up to eight gas extraction bores and associated handling systems which are co-located on the same drilling pad. The deviated wells run in different directions from the well pad to tap gas in the narrow, multiple coal seams lying above each other, each bore running up to 800 metres along the coal seam. This reduces the above-ground imprint of roads and water and gas-gathering pipelines, as well as water separation and pumping station facilities. This enables gas extraction from a very large area – about 2000 ha for each planned well pad.

The proposed expansion by Origin, by drilling 7700 wells and installing 6800 km of gas and water pipelines, will have a large "development footprint" which is "likely to alter local patterns of alluvial recharge, … [and] disrupt riparian corridors" (IESC, 2022a, p. 7). The disruption of surface water flows is likely to have a drastic effect on the vulnerability of the land to erosion during extreme weather events, which is almost certain to increase with climate change. Similarly, for Santos (IESC, 2022b) with its proposed 116 wells, dam(s) storing produced water are susceptible to overtopping in extreme weather with likely highly deleterious consequences downstream.

Gas operators have started deviated drilling on the Darling Downs Condamine River flood plain, sometimes where the landholders do not want any part of this. The concerns of landholders are several, but primarily that it will result in loss of water from the aquifers which historically have supplied irrigation water – 130 GL in 2020–2021 – to the farmers in the Condamine Balonne area (DNRM, 2012; DNRME, 2018; DRDMW, 2021), an area about 1.37M ha and 7.9% of Queensland (DES, 2018, 2022a). The Surat Gas Project in this area covers ca. 250,000 ha, a major part of it in the Central Condamine Alluvium which comprises more than 445,300 ha (DES, 2018).

Other concerns include that CSG extraction is causing subsidence (see Subsidence section of this paper; Australian Government, 2014b; OGIA, 2022; GFCQ, 2022d) which severely constrains the productivity of cropping land and ease of conducting farm operations. There is concern that tractors will bog in subsided areas as water will pond there; that soil compaction is potentially greatly increased (Al-Ahatib Mohammed et al., 2021); and that channels created by the compaction will disturb flood erosion control (Queensland Government, 2015).

For farmers, both directional and vertical wells are an inconvenience as they have to manage farm operations around CSG-related traffic to wells on or adjacent to their farm. For example, gas-related activity can constrain crop-spraying times, introduce weeds on company vehicles and trigger erosion during rainfall events around roads and gathering pipes (Dart, 2020).

Destination and Quality of Extracted Water

The water in parts of the Walloon coal measures is less salty than the main body of CSG-produced water and has long been used for agriculture. In the Surat Basin Cumulative Management Area, more than 340 of these bores into the Walloons and other aquifers are classified as Immediately Affected Area (IAA bores), having lost so much water pressure to the CSG extraction process that they are no longer reliable for use by landholders (OGIA, 2022). The CSG companies are required to 'make good' lost water (DES, 2021a), but this has often been a most unsatisfactory outcome for the landholder (e.g. AgForce, 2021). Under 'make good' arrangements, if the CSG extraction impairs the capacity of a water bore, the resource holder must make good the impairment in the way outlined in an agreement between the company and landholder or water user. This often involves drilling the bore deeper or drilling another into a deeper aquifer. This raises issues about the comparability of the water quality and the cost of pumping it. If this option is not available or is unacceptable, a monetary recompense may be offered, or water can be trucked to the site. Calculating the value of a resource not available into the 'forever' future is, however, problematic.

Associated wastewater on the other hand is often very salty and unusable until re-processed, such as by reverse osmosis (RO) plants. Reverse osmosis removes most of the salts, leaving other salts (mainly sodium chloride and bicarbonate) to somehow be disposed of safely. The DES has established a stakeholder working group of about 42 persons to examine this issue. But after three meetings there has been no decision as to how to allow the CSG companies to do this, *some 25 years after the Queensland Government encouraged the development of CSG mining* (DES, 2021b) and at least 15 years after the Department deemed evaporation ponds to be an unsatisfactory solution (Edwards, 2006b). Regardless of whether the produced water is deemed to be waste or a valuable agricultural asset, as next analysed, the current regime is unsatisfactory.

Regarding the Produced Water as Waste

Much of the CSG-produced water is currently stored in large, surface-dam constructions by the CSG companies, supposedly briefly, until treated to remove the salts by RO and afterwards in other dams prior to distribution for use (Morris, 2022). Because the RO water is pure, it can be shandied with saline water to bring it to a salinity level that is deemed not to be damaging to crop growth and soil processes. A contingency discharge to a watercourse is allowed only when beneficial use is not available for the quantity in surplus and should be allowed only under the Coal Seam Gas Water Management Policy 2012 (DEHP, 2012) on special exemption in the case of heavy rainfall events causing flooding and potential overtopping of the holding dams (Australian Government, 2022), but this is likely to change surface water quality, a key impact identified by the IESC (2022a).

While the resulting shandy may be tolerable for cattle to drink or crop plants to grow, at its heart it is not an adequate or environmentally sustainable remedy. Salts that had been immobile are being brought to the surface and mobilised into the upper catchment of the Murray-Darling system, which downstream is already carrying a burden of sodium salts far greater than desirable.

The most recent public Queensland Government Coal Seam Gas (CSG) Brine Management Action Plan draft report (DES, 2022b), in 2020 to the Murray-Darling Basin Authority for their audit of the salt loading from Queensland, recorded 26 brine ponds with a combined total of 18 GL and having an electrical conductivity (EC) ca. 40,000 μS/cm (see Glossary in Supplementary Material for more information on salinity levels). There are now understood to be at least another nine ponds with a combined total of ca. 14 GL. The final volume of salt calculated from the proposed volume of water from more than 22,000 proposed wells would be about 5–6 million tonnes. Disposal of up to 15 million tonnes of this salt, as well as fracking waste products (see Note 5 in Supplementary Material), was approved on

13 November 2013 by Maranoa Regional Council, for a site near Stockyard Creek at Baking Board Hill near Chinchilla, to We Kando Pty Ltd.

The RO plants themselves require much energy to operate (see Note 6 in Supplementary Material). In addition to all the water-related difficulties of disposing of this water, there is an emissions-related challenge which will become only more difficult as national imperatives to reduce emissions intensify.

Regarding the Produced Water as an Asset

The current process for disposing of associated water has resulted in an economically inefficient and inequitable distribution of a *public asset* that is contrary to the principles outlined by the National Water Commission (2014). The opportunity to use the produced water in support of water reform in the Murray-Darling Basin has not been recognised by the Queensland Government in the regulations underpinned by the *Environmental Protection Act 1994* (Qld) (EP Act) which designates it primarily as a waste product (DES, 2021; Monckton, 2018; Monckton et al., 2017; Business Queensland, 2022).

Currently produced water is provided to Chinchilla Weir (managed by Sunwater) and to irrigators near the major water treatment plants, such as Kenya located near Chinchilla, and a few feedlots and industrial users. Relatively few irrigators are contracted to take an agreed volume of water on a regular basis. Anecdotally, it appears that farmers are reluctant to sign up to re-use this recycled water, because they may be required to take it even when it is raining and irrigation is not needed. In particular, difficulties arise in a wet year with high-cost penalties imposed by the CSG company if the water is not used. Certainly, irrigators can benefit in that the cost of water is considerably less than the cost of other water in the market.

However, diversion of purified water into irrigation is of only temporary benefit to growers because it can continue only so long as seams within range of the local RO plant are being dewatered. This time period may not be sufficient to justify capital investment in farm irrigation plant.

Subsidence

Removal of the water and gas from the coal seams leaves an expanding zone of low pressure yielding decreasing volumes of water and gas as more is extracted. Landholders are worried that water from the aquifers that they use will drain into the de-watered coal seams, which now have a lower pressure profile. This induces flow from the water-filled pores above into the zones of lower pressure in the coal seam pressure ‘void’. The water pressure (buoyancy) in this material above the coal seams functions to maintain the spatial relationship of the layers above the coal seams. The strata above the coal seams are now less supported, and their downward pressure (determined by gravity and weight/density and elasticity of the material) moves them into the ‘void’ below. This subsidence may or may not be transmitted all the way to the surface, depending on the thickness and hardness of the sandstone and alluvium strata which lie above the coal seams (IESC, 2014; Galloway, 2016; Marker et al., 2016; GUSGS, 2019; Pan et al., 2022).

A major concern of farmers about subsidence results from the lack of sufficiently accurate systems or requirements for measuring baselines on cropped land before drilling starts and the soil profile changes. The *Underground Water Impact Report for the Surat Basin Cumulative Management Area* (OGIA, 2022) has minimal recognition by way of definition, or of the cost penalty that subsidence imposes on farm operations. Further, the report does not concede that this subsidence will persist over time and affect the status of the land, virtually forever, or that it cannot be rectified. Subsidence makes the land prone to erosion, a major issue on the vertosols of the Darling Downs where farmers have, from the 1980s, developed better land management and cropping systems to overcome the sheet erosion that occurred during rainfall events.

The extraction of water by farmers from aquifers above the Walloon measures could also result in subsidence. However, the irrigators on the Central Condamine, such as the members of Central Downs Irrigators Ltd, have considerably cut back their use of this water for irrigation to meet the government-permitted extraction limits in their water use licences (Business Queensland, 2021). The limits are specified to balance offtake and recharge as an aid to sustainability. Again, ongoing measures of the field surface status would support this modelling of recharge rates.

Arrow Energy has directionally drilled under several farms in the Darling Downs near Chinchilla and Dalby and commenced to extract gas without informing the landholders, as mentioned above. Since this latest round of new drilling, subsidence has been reported in a cropping field, leading to ponding, waterlogging and compaction as the affected soil surface is now uneven and moister. Moist vertosols are compacted more than drier vertosols by machinery traffic (Al-Shatib et al., 2021). Such subsidence can have a major effect on productivity as the precision agriculture practised relies on adequate drainage in fields of shallow slope.

Methods to measure subsidence have limitations. Subsidence is currently assessed by CSG companies and the OGIA by the Interferometric Synthetic Aperture Radar (InSAR). Images captured by a satellite system can detect dynamic ground position changes such as deformation of the earth's surface. Radar signals from the satellite are bounced back from the ground to the satellite and captured by the sensor during different orbits (USGS, 2014, 2018). Small differences in the distance from satellite to the ground as the land surface moves up or down can be detected. However, the dynamic nature of cropping – with variable vegetation such as growing cotton or stubble left in conservation tillage systems or harvesting, or a rough ground surface after ploughing, or the swelling and shrinkage of heavy clay vertosols with rain or irrigation – limits the usefulness of InSAR measures of subsidence in cropping land, particularly where there may be several crops a year. The method is acknowledged to have limitations in assessing the small, early levels of subsidence which increase over the years as the earth layers compress with the reduction in pore pressure as gas and water are mined (Pan et al., 2022).

The lack of appropriately detailed baseline measurement before CSG mining starts has been pointed out forcefully by recent reports to the Australian Government from the Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development. Baseline measurement is required for the proposed large expansion of gas wells in the Surat Management Area by Origin (IESC, 2022a) and Santos (IESC, 2022b). The regional effect of such development is critical to assess. Further, these reports note the high risk that cumulative impacts will exceed threshold ecohydrological requirements, particularly where groundwater drawdown is predicted over several hundred years.

Subsidence following extraction of groundwater has been observed in coastal cities and agricultural regions worldwide, examples being Jakarta and Lagos (Galloway & Burbey, 2011; Gambolati & Teatini, 2015). In the San Joaquin valley in California, the land subsided (compacted) by about 9 metres between 1925 and 1977, a process attributed to withdrawal of groundwater. As noted by Parker et al. (2021, p. 1): "Long-term, irrecoverable subsidence is associated with inelastic compaction of aquifers."

It is entirely plausible that mining for CSG is similarly creating large 'voids' with similar geophysical effects. Further, recent modelling of subsidence in China and the US indicates that the earth fissures that can also develop with water extraction from pumping are likely to be caused by an aseismic event related to a ridge in the base of the pumped aquifer (e.g. Li, 2021; Nardean et al., 2021). If such a fissure developed under a CSG salt-holding pond, it could have catastrophic consequences through salt release to the environment and, if on a farm, loss of potential irrigation and crop production. Another model shows how spatial variation in subsidence in alluvial basins can be related to the aquifer drawdown levels (Chu et al., 2021).

Legacy Coal Exploration Wells

Also contributing to the leakage of water are the exploration bores for coal mining. These bores are not often on the OGIA register and are commonly not monitored and not properly capped. Appropriate 'Construct and Abandon' practices have often not been followed, leaving the unlined bore as a channel for water to flow into or from the aquifers they pass through, facilitating drainage into depths below the aquitard above the coal seam and into the coal seam itself (Mallants et al., 2018). The CSG and water extraction can occur quite close to these abandoned coal bores. The coal cleat space from which the gas is withdrawn may continue up to the abandoned bore site so that aquifer leakage would be facilitated through the unplugged coal bore once the pressure in the seam is reduced by the CSG extraction. The Office of Groundwater

Impact Assessment has identified 2200 such coal exploratory well holes in the Springbok Sandstone aquifer, although there are at least 18,000 coal holes in the Surat Basin (OGIA, 2021). It is likely that many of these are not capped and plugged with cement (Mallants et al., 2018; Morris, 2020).

Some of these coal bores penetrate through to the Hutton aquifer(s) below the seam. These coal holes are also a conduit for gas and water emanating from the coal seam depressurised by CSG extraction to belch from the ground surface, where there is sufficient pressure to reach the soil surface, as has been anecdotally reported (Clarke, 2022; Smee, 2022a).

Such a situation has recently occurred near Origin Energy CSG wells near Chinchilla on Western Downs properties. Origin voluntarily capped a few of these coal bores that were emitting fugitive methane emissions and large amounts of salty water near their CSG wells. However, it is not clear how many coal bores Origin plugged with cement (the proper method) or whether this was pressure-tested to see how effective the plugging was (Long, 2022b).

Leakage from Previously Stable Dams

Large losses of water have recently been observed from a 1200-megalitre, seven-metre deep, surface ring tank (dam), used for irrigating crops such as cotton on a property near Dalby. The losses were much more than the pan evaporation rate for the location and greater than normal seepage from previously well-sealed tanks, including one nearby of similar depth on the same property. The dam was directionally under-drilled for a production well under almost the full extent of the dam floor in 2018 by Arrow/Shell (ABC, 2021, 2022; QCL, 2021).

This loss can be attributed to a change in the hydrological profile below the dam, caused by loss of hydrological pressure and then loss in the support of the dam's clay floor seal. The base of large ring tanks across the north-west of New South Wales and southern Queensland is supported by a dome of saturated soil that is contiguous with the aquifer and is stable, as crops or trees are not extracting water from it. Leakage into and from the dome is minimal, as lateral underground flow out to less-saturated soil away from the dome is small and slow (Cottoninfo, 2018).

Walloon coal measures are as shallow as 60 metres below surface at this location, which is an area where the overlying Springbok Sandstone has been identified as immediately affected by groundwater depressurisation from CSG extraction (OGIA, 2022). Once the strata below the dam are disturbed by extraction of gas and water, they will subside and drainage from the groundwater dome can follow.

Aquifer Connectivity

Any movement of water out of the coal seam by drainage to the aquifer below would likely contain measurable quantities of a range of polluting chemicals including salt and the BTEX chemicals, even though their concentration may be below the minimum-level, permissible standards for drinking water. Benzene should be less than 1 part per billion, and other chemicals 300 to 800 ppb (DES, 2020). BTEX compounds are not permitted as chemical additives in fracking fluid in Queensland, although the long list of chemicals used does contain some unspecified compounds (Shell, 2022).

Shell/Arrow Energy has sponsored research by GISERA and The University of Queensland's Coal Seam Gas Centre (now Centre for Natural Gas) at a few wells and bores on the vertosols of the Condamine River Alluvial land, with the aim of assessing whether the overlying aquifer is connected to the coal seams by faults and fissures (Owen & Herbert, 2020). The Office of Groundwater Impact Assessment (2016) had reviewed the information on connectivity and concluded that the level of hydraulic connectivity was low.

A subsequent pilot study commissioned by Arrow, and conducted by CSIRO, attempted to use isotopic analysis of noble gases and conventional tracers to support this, but the small number of wells sampled in the study (two – and then only at three or four depths) and the differences between them indicated that each was only a snapshot in time and place and that the sampling methods for the gases need to be improved. It was acknowledged that de-pressurisation of the coal measures by CSG extraction over time could cause a change in the profiles (Suckow et al., 2021).

Research conducted by Iverach et al. (2015) at the University of New South Wales also examined gas and water movement between the Walloon

CSG and Condamine River Alluvial aquifers and measured the isotopic constitution of the bore waters and gases in several wells. The study used 16 irrigation bores near Cecil Plains, Queensland, for the data for modelling the biogeochemical processes to indicate connectivity of the methane gas in the well with the coal seam.

Genetic sequencing and isotopic analysis of bore waters in CSG development areas in the Condamine Alluvium aquifers identified methanotrophic bacteria, which in natural conditions would be expected to be out-competed by sulphate-reducing bacteria in the alluvial groundwater. Their data thus suggest that methane (as a gas or in groundwater) was being introduced into the aquifer from CSG-bearing layers through inter-aquifer leakage and/or surface leakage of CSG wastewaters (Iverach et al., 2017).

Spot Research Does Not Necessarily Scale Up

The studies described above were carried out at a very small number of locations, scattered over a vast area of agricultural lands in the Surat Cumulative Management Area, including the renowned Condamine flood plains, which are about to be mined for CSG. Some 465 out of ca. 8000 bores in the Surat Basin are on the OGIA register of bores whose water height (pressure) is being monitored, some by the gas companies. The Office of Groundwater Impact Assessment now meters water levels in 30 of these wells. It is unclear how confidently this spot research, and well data held in multiple agencies (OGIA, 2019a; OGIA, 2021), can be extrapolated and trusted to scientifically adduce (as posited by OGIA and the GasFields Commission):

(a) that there is low permeability and little vertical connectivity of water between the aquifers now as the “intervening aquitards have not yet been subjected to significant vertical head gradients” (OGIA, 2022, p. 86) (but this does not hold if aquitards are not present or are variably impermeable or not homogeneous across their whole expanse in the Basin); and

(b) that this will always remain so, in perpetuity, regardless of seismic events.

This contention of the OGIA that all is well is despite the large changes in the Walloon coal measures where the water level has decreased as a result of extraction. This extraction has created zones hundreds of metres in diameter (and maybe even larger) of CSG depressurisation around the gas wellheads and altered the head pressure between the coal seam and aquifers above. This creates a gravitational force for water to flow from the upper aquifers into the huge, physically unstable, mechanically unsupported and depressurised zones in the coal measures (OGIA, 2021). The leakage into the coal seams is estimated by OGIA to be about 1300 ML per annum in the Surat Basin, but this volume is bound to increase as the number of wells in the gas production zone rises to a predicted 22,000 from the current ca. 8000 (OGIA, 2020; OGIA, 2022).

This leakage from aquifers and gas migration may occur along a range of pathways, including along existing faults. Such pathways have been meticulously and comprehensibly documented by CSIRO (Wu et al., 2016). Along with well failures during operation, they will continue to occur as materials such as cement and metal casings deteriorate with age. If the well is an exploratory one and is then plugged above the coal seam, water and gas will pass if the integrity of the temporary plug gives way and if there is an annulus (space) between the casing and the rock formation.

Inadequacies of Regulatory Regimes

The CSG industry is subject to an extensive and complex network of statutory provisions, broadly clustered into gas tenure, environmental authority, EPBC Act assessment, and private contracts (see Note 12 of the Supplementary Material). A detailed explication of these provisions is beyond the scope of this article. Instead, we highlight some inherent weaknesses in the regime that collectively they create. A key weakness is the reliance on adaptive management, which is now the preferred approach of the Queensland Government towards the burgeoning CSG industry (DES, 2020b; see Note 13 of the Supplementary Material). Adaptive management, however, requires active involvement by both the company and the government for the lifetime of each installation. This is conspicuously lacking, especially once gas extraction has finished, as the company loses interest and the Departments cannot summon up the skilled staff necessary. Adaptive management is a ‘learning by doing process’, which is in considerable tension with the precautionary principle.

Landholders' Concerns: A Recapitulation

Affected landholders, particularly in the Condamine Alluvium, have made representation to regulators and the press about the lack of progress on several issues, listed below and reported by Lock the Gate (see Note 2 in Supplementary Material; Dart (2020); Queensland Audit Office (2019); EDO (2021)):

1. Lack of subsidence monitoring or baseline assessment and apparent lack of response from agencies at either state or federal levels of government or appreciation of the urgent need for addressing subsidence issues.
2. Directional drilling of landholdings from adjacent properties without a CCA or other agreement with the landholder and often without notification nor detail of location of the well and provision of well logs on request.
3. Alienation of good-quality agricultural land, a natural resource in limited supply, against the government's previous statements that it seeks to ensure the land's protection.
4. Aquifer leakage and inadequate pre-assessment and regulation of impacts or 'make good' provisions.
5. Inadequate or non-existent capping and plugging of exploration bores for coal mining, leaking voluminous quantities of fugitive methane from the legacy bores and through waterways, and belching through ponded water in cropped fields (Smee, 2022b); and further, resulting in possible contamination by salt and BTEX-type chemicals of water used by cattle and households.
6. Potential loss of aquifer water from unlined and unplugged gas exploration wells.
7. Disposal of the millions of tonnes of brine and management of the 42+ very large dams/ponds holding brine.
8. The role of the GasFields Commission in not protecting the interests of landholders and diluting the government's accountability for regulating the gas industry; also, the Commission's Board composition, holding two ex-gas industry representatives.

On 8 February 2022, the GasFields Commission (GFCQ, 2022c) called for immediate action to resolve ongoing coexistence issues and community concerns from Arrow Energy's Surat Gas Project. The Commission, in their review of the RPI Act assessment process finalised in October 2021, found a lack of clarity and transparency around gas companies' compliance and noted that subsidence was a "significant concern" (GFCQ, 2021c, p. 1) for landholders. It called on the State Government to enter the dispute and "provide details of its expectations on compliance and how resource companies are meeting these statutory requirements" (GFCQ, 2021c, p. 1).

When Arrow reportedly under-drilled properties from a well pad on a neighbouring property without a Notice of Entry or a CCA in place, the farmers were given no advice by the Department of Resources as to their rights or information about the bore's history and location, despite repeated requests. Belatedly, the Department fined Arrow (Shell) \$1 million for not having a Notice of Entry but indicated that it was a court concern if a CCA was not in place (Long, 2022a; Queensland Government, 2022).

Queensland Audit Office's Red Flags

The Queensland Government has fragmented statutory roles around gas activities (see Note 14 of the Supplementary Material). The Queensland Audit Office (2020) report *Managing Coal Seam Gas Activities* critically reviewed the approach by the regulators in the Department of Natural Resources, Mines and Energy, the DES and the GasFields Commission in managing the increasing scale of CSG developments. It recommended that the Commission review the RPI Act assessment process to determine whether the process adequately manages coal seam gas activities in areas of regional interest, including consideration of stakeholders' concerns about exemptions and inconsistent definitions of land (Recommendation 8 and Chapter 1: Regulating the industry).

A number of specific matters requiring improvement were identified in their report, notably:

1. The need for increased clarity of regulation of gas industry activities, removing inconsistent statutes dispersed across relevant agencies,

improving industry attention to risk-based planning and improving regulation of the impacts on priority agricultural land.

2. Dispersed and inadequate data on activities and compliance issues across agencies; and limited data sharing, hindering the collective understanding of regulatory effectiveness and industry compliance.
3. Limited enforcement, rather a focus on education, but with too few experienced staff to do this adequately and competently.
4. The confusion of stakeholders as to the role of the various entities involved in overseeing the gas industry, including the regulators and other Departments, the Commission, the Land Access Ombudsman and the Land Court; confusion about where to seek information or compliance action and how to deal with disputes. Four Departments are involved in the regulation of effects on agricultural land, leading to inconsistencies of land classifications and ways of dealing with land use conflicts. Key issues, such the health and safety of landholders, are falling through the procedural gaps.
5. Where baseline data exists, it is often not shared with landholders because gas companies regard it as 'commercial in confidence', advantaging them in landholder negotiations. Landholders are restricted from sharing CCAs so that neighbours have no benchmark data from which to negotiate their own deals.
6. Perception by key stakeholders of the lack of independence of the Commission.

Inadequacies in the Evolution of the Regulation of Agricultural Land

The regime introduced by the 1992 *State Planning Policy on Good Quality Agricultural Land 1/92* is now arguably weaker than ever. It is certainly more complicated. The original State Planning Policy 1/92 specified land classes and their potential uses. The land resource mapping underpinning the policy was deemed insufficiently detailed or prescriptive, and this led to the *Strategic Cropping Land Act 2011* (Qld) (SCL Act) which provided for designation of land into classes, a measure which weakened protection of some of the lower-quality soils. Under the Newman Liberal National Party Government (2012–2015), after the rapid expansion of the industry without proper assessment of regional effects such as aquifer integrity, the SCL Act was repealed. Later, the *Land Access Review Implementation Report* (2013) led to the RPI Act. The Act claims to seek to strike a balance between protecting priority agricultural areas and strategic cropping areas and managing (and supporting coexistence with) mining and petroleum activities (Taylor & Hunter, 2019). Under the RPI Act, resource activities may require a Regional Interests Development Approval (RIDA). The goverment recently provided updated guidance for local governments by which the reference to coexistence merely states that "… gas resource development operations and other land uses are facilitated" (DSDILGP, 2021, p. 67). 'Balance' can only mean a compromise; and that can only mean that the pre-existing activity (farming) loses.

The RPI Act is not proving to be effective in moderating the industry, with public notification not always required for a RIDA application, and only to directly affected landholders holding appeal rights over decisions. At the time of writing, no application for a RIDA has ever been refused, and only minimal, if any, conditions are placed on the approvals.

Gas operators are able to self-assess whether or not an exemption applies to their activities without any notification process, and we are not aware of any regular procedure in place by the government to check the validity of the self-assessment. In the recent review of the RPI Act's operation by the GasFields Commission, discussed above, the recommendations laudably seek to improve transparency around the self-assessment, but there was no recommendation to remove this self-assessment process (GFCQ, 2021b).

The RPI Act application often comes after the awarding of the environmental authority (EA), by which time the momentum built up in the process makes any rational assessment of the implications virtually impossible. The assessments for the EA and the petroleum tenures do not specifically require assessment of the impact of the activity on agricultural land and its productivity, although arguably this could be assessed as part of the 'public interest' element of the standard criteria for site-specific EAs. The regional or cumulative effects of the CSG mining activity on agricultural land are not clearly considered in the awarding of the project-by-project EAs.

There are various points in the environmental legislation and the petroleum/gas legislation at which ministerial or officer-level discretion could be exercised in favour of the 'public interest', such as the "any special criteria" for issuing an authority to prospect in s. 43(1)(a) of the P&G Act (p. 83). It is open to the Minister to promulgate policy guidelines that would give a mandate to assessing officers to apply special criteria, without any need for legislation, but none are known.

Precautionary Principle

The 'precautionary principle' was established as national policy when the state and Commonwealth governments signed the *National Strategy for Ecologically Sustainable Development* in 1992 (AGPS, 1992; Emmery, 1993). The precautionary principle reads: "Where there are threats of serious or irreversible environmental damage, lack of full scientific certainty should not be used as a reason for postponing measures to prevent environmental degradation" (Emmery, 1993, p. 31). The principle is reflected in the EPBC Act, including the Significant impact guidelines 1.3: Coal seam gas and large coal mining developments – impacts on water resources; and state laws such as the EP Act.

Evidence from Australia and overseas has provided sufficient warning signals to justify invoking this principle and at least pausing the industry until the potential weaknesses in the regime are plugged. A 'pause' has been applied by other jurisdictions in Australia via moratoriums on the industry and reviews of some gas activities, which has led to considerable legislative reform in the Northern Territory, Western Australia, New South Wales and Victoria (IESC, 2014; Victorian Government, 2015; Luke et al., 2018; Labinsky, 2019).

Contrastingly, the Queensland legislation is predicated on encouraging exploration in order to realise the state's natural assets, then on allowing companies who have invested in identifying a resource to proceed to a production lease, if they can demonstrate financial viability and their own financial capacity. The legislation places the onus on the environmental assessors to justify refusal and, where significant concerns are raised, operates on the presumption that they can be addressed by conditioning and adaptive management rather than refusal. This reliance on adaptive management is often not based on sufficient upfront environmental assessment to properly understand the baseline environment and ensure that the management and monitoring techniques conditioned are appropriate to the site and environmental circumstances (Rose & Pointon, 2018).

Clearly, the best time to apply the precautionary principle and assess the possible risks of a project is when considering whether to issue an authority to prospect. Once a company has invested in exploring and proving up the viability of the field, the pressure to allow the extraction to proceed to maturity is considerable. Unfortunately, the EP Act allows environmental authorities for exploration activities to go through a 'standard application' process, with no reference to the precautionary principle in the criteria or conditions. This is particularly concerning given the emerging evidence on groundwater aquifer interactions and the significant hydrogeological impacts of the industry.

That saline effluent is still being stored in large dams some 25 years after this was deemed to be an unsatisfactory method of permanent disposal says much about the willingness of the Queensland Government to abrogate the precautionary principle. Although the dams are plastic-lined, there is no precedent for confidence that such material will not become brittle in sunlight and/or be able *in perpetuity* to prevent the escape of salt into the soil and run-off.

Carbon Dioxide and Methane Emissions

Atmospheric carbon is not regulated as a pollutant under the *Environmental Protection (Air) Policy 2019*, so the propensity of a coal seam gas operation to release methane or carbon dioxide need not be assessed under an environmental authority. There are no legislated limitations on these emissions, nor need emissions be monitored and reported as a standard condition. The carbon profile of the industry is left to a federal requirement that the industry reports their emissions (often modelled rather than monitored on site) to the Commonwealth's Australian National Greenhouse Accounts, a demonstrably inadequate means of accounting for and mitigating emissions.

Fugitive emissions are produced at numerous points of the CSG production chain. While gas is touted as a 'transition fuel' between coal-fired electricity and renewables, its emissions profile is lower than coal only if counting is confined to the end-user activity (Lafleur et al., 2016; Swann, 2020). Significant volumes of methane gas are vented or flared (burnt) before a well is connected to the pipeline grid. Once a well is producing, it cannot easily be halted without flooding the seam (requiring the dewatering to be repeated), so considerable quantities of gas can be wasted.

Further, existing faults and fissures in the Condamine Alluvium may allow gas from the seam to escape through the earth surface. Depressurising the underlying coal seam during mining appears likely to have facilitated gas bubbling to the surface into the Condamine River through existing and newly created fissures and faults in the strata above the coal seam (Mudd, 2012; GISERA, 2017). The gas in the coal seams is held in place by the groundwater pressure, which is usually higher than for the Condamine Alluvium aquifer above the seams. Gas bubbling has been observed in the Condamine River and its tributaries for more than 100 years. But the difference now is that gas is anecdotally observed much more frequently and abundantly than historically, and the gas bubbles can even be easily ignited (Williams, 2016; Fritz, 2016).

Insurance

Australia's largest insurance company, Insurance Australia Group (IAG), has said it no longer will cover farmers for any non-farming related public liability if they have CSG infrastructure on their property, including risks arising from groundwater contamination or loss, even if there is a CCA between the landholder and the gas company (Morris, 2021a). If this policy is confirmed and becomes a general practice of insurers, it signposts a transfer of risk from companies with extensive geological, hydrological and engineering expertise and large financial resources to landholders, the stakeholder entity least capable of managing the risk. Undertakings by the gas companies to promise coverage under a self-insurance scheme are valid only so long as the companies remain in existence, retain a legal connection to any properties affected and choose to honour the agreements. The GasFields Commission working group has brokered a *Landholder Indemnity Clause* which does not address major concerns such as identifying the landholders' land rights into the future from damage caused by the mining, especially with regard to underground water resources, subsidence or under-drilling without a CCA (GFCQ, 2022b).

Self-regulation Prior to Environmental Assessment

The integrity of the environmental assessment of gas activities in Queensland has many questionable aspects, which is especially concerning given that the footprint of CSG mining is the largest of any mining activity in Queensland. The extent of company self-assessment in the procedure for applying for an EA is particularly troubling (see Note 7 in Supplementary Material). The standard EA for an authority to prospect typically requires self-assessment against broad eligibility criteria and standard conditions. If it is considered that the company meets these criteria and conditions, DES cannot refuse the application, regardless of outside circumstances that may make the application inappropriate (EP Act s. 170). The progression from an EA for exploration to an EA for production is often approved by minor or major amendment of the exploration EA. Minor amendments are not publicly notified, and the Department has a discretion as to whether to publicly notify major amendments. Thus, major amendments to EAs may be approved without any public scrutiny.

An example is that the number of wells allowed to be drilled by the Santos Mahalo gas project in the Bowen Basin of the Surat Cumulative Management Area doubled to 383 and two new tenures hundreds of kilometres from the previously approved tenures were added, by amendments approved in 2017. This project has never been scrutinised through an environmental impact statement. These major amendments were not notified to the public. The project is located on strategic cropping land and priority agricultural areas and hence should seemingly be regulated under the RPI Act, but no application for assessment appears to have been lodged, and it is not obvious what exemption may apply, if any. The RPI Act relies heavily on self-assessment by proponents, even as to whether an exemption applies.

Self-regulation Substitutes for Compliance

Currently, regulators do little independent field monitoring, rely on gas companies to self-regulate and report, and act on complaints only if they choose to do so. The *Mineral and Energy Resources (Common Provisions) Act 2014* was enacted to streamline the various mining and resource laws and facilitate negotiation by resource companies and landowners around land access by the resource tenure-holder (see Note 8 in Supplementary Material).

There is scant information about compliance of companies with the conditions in the EAs, as DES does not publish details of "penalty infringement notices" (DES, 2021d), which are the most common compliance tools used. Companies in turn are not required to publish their response or their compliance with the EA conditions in their annual reports. In Queensland, compliance activities are not required to be reported in annual reports from resource operators, as is required in other states. Companies in the main self-report their compliance, and as Departmental on-site audits are infrequent compared to the number of projects operating, the likelihood of recording breaches is slight.

Reporting of fugitive methane and carbon dioxide emissions, let alone all Scope 1, 2 and 3 emissions, is a case in point. Current fragmentary evidence indicates they are grossly under-reported. For example, CSG companies have been shown by infrared optical gas photography to illegally vent rather than capture the gas that accumulates in the water-gathering lines (Dougall & Evans, 2020). In 2021 an aerial survey of the Surat Basin, Queensland's main CSG region, discovered that methane emissions were two to three times higher than has been reported (Neininger et al., 2021). Transparency would help to ensure that compliance is taken seriously, improving community confidence in the government, industry's social licence and respect for the law.

Conclusions

The life expectancy of the CSG industry in the Surat Basin is 30 or more years according to the production permits already issued for the Surat Cumulative Management Area (OGIA, 2019). The 2021 draft *OGIA Underground Water Impact Report* for the Surat Cumulative Management Area acknowledges that there are likely to be impacts for landholdings used for dryland and irrigated cropping. Yet this is inconsistent with the stated Queensland Government strategy to double agricultural production by 2040.

Landholders have been farming on the Darling Downs for well over 150 years. Done sustainably, farming arguably could continue indefinitely, putting aside risks posed by climate change. Coal seam gas mining threatens the sustainability of production of food and fibre in the Surat Cumulative Management Area, especially on the Darling Downs and Condamine Alluvium. Through poor regulation of impacts to ground and surface water resources, risk of subsidence and inadequate management of CSG-produced water, these precious agricultural lands are being put at long-term risk, threatening the future of agriculture in the region as well as the natural environment.

The dispersed, unclear regulation across multiple agencies of the interaction between the gas industry and landholders has created significant confusion and led to a loss of social licence of the gas industry in the areas it operates. This is heightened by failures in the statutory regime to protect the environment and landholders' interests by adequate assessment upfront of activities prior to approval. The focus on 'coexistence' has been undermined by this poor regulation and governance, which is disregarding the precautionary principle and the property rights of landholders. Where landholders are coerced into agreements under significant power imbalances, these agreements and the broader regulatory framework are not protecting the long-term viability of agriculture in one of Queensland's prime agricultural regions and are eroding trust in governments.

Given the accelerating rate of decarbonisation of the national economy and the significant greenhouse emissions of the gas industry, attention must now be given to phasing down this industry and remediating its infrastructure, but no feasible path towards securely stabilising in perpetuity the thousands of wells being drilled is visible. Nor is it clear that the cost of remediation, even if that were practicable for bores hundreds of metres deep, will be charged to the activity causing the need.

The performance-based statutory regime (which does not envisage refusal of applications and does not adequately monitor performance), the fragmentation of accountability across multiple authorities, the absence of any systematic resolution of landholders' concerns over many years and the statement in 2021 by the Acting Director-General of the Department that companies, not the regulator, are responsible for gaining the community's trust, are all evidence that the Queensland Government conceives of its role simply as facilitating this problematic industry and that the 'public interest' which the electorate appoints it to protect has no dimensions other than the narrow one of gas production.

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Recent Initiatives for Biodiversity Conservation on Privately Tenured Rural Land: An Introductory Survey and Discussion

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Abstract

In Australia, and across the world, there is growing interest in protecting biodiversity on privately tenured rural land. New design frameworks and new funding models, including market-driven opportunities, are being actively pursued by Australian governments at all levels. Recent critiques have exposed a number of design flaws in some of these programs. This makes it timely to consider alternative models, both national and international, with a view to ascertaining what lessons, if any, Australia can learn from these examples. In pursuit of this objective, this article describes and comments on some alternative models for securing land for biodiversity conservation on privately tenured rural land in Australia and overseas. We survey three different schemes in Australia and briefly describe a variety of schemes in five overseas jurisdictions. These schemes were selected because they include some approaches that are different from those in the Australian case studies. Overall, we found that whilst Australia has made some strides towards expanding the range and type of programs available to secure biodiversity conservation on privately held rural land, there are more options and some promising approaches with which Australia is yet to engage. Overseas jurisdictions can provide valuable insights and additional ideas.

Keywords: biodiversity conservation, nature-based solutions, rural land, private tenures, funding schemes

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Introduction

Biodiversity conservation initiatives are on the move. In the past, declaring, protecting and managing a dedicated system of national parks and reserves was, for the most part, accepted as a routine budget item for responsible governments (Bradsen, 1994; Bates, 2019; DAWE, 2022). In recent years, however, new sources of finance and new management models have leapt to centre stage. There is growing interest in protecting biodiversity on privately tenured rural land and continuing talk about developing market-driven opportunities to help finance initiatives in this area (Carbon Market Institute, 2017; Bates, 2019; Godden & Peel, 2019; Australian Farm Institute, 2021).

At the same time as new funding opportunities are being explored, the rationale for biodiversity conservation is also expanding. The International Union for Conservation of Nature (IUCN), for example, advocates for 'Nature-based Solutions' which value the conservation of ecosystems and biodiversity not simply as ends in themselves, but

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as a means of addressing a number of related and connected sustainability issues (IUCN, 2022). Nature-based Solutions "use the power of functioning ecosystems as infrastructure to provide natural services to benefit society and the environment" (IUCN, 2022). Nature-based Solutions recognise and promote the role healthy ecosystems play in addressing issues as varied as deteriorating agricultural productivity, biodiversity loss, the mental health crisis and the challenge of climate change (Seddon et al., 2020, 2021; IUCN, 2022). This re-positioning of nature conservation brings biodiversity and ecosystems management programs centre stage to debates about resilience, sustainability and climate change (Portner et al., 2021; IPBES, 2022; IUCN, 2022).

This article describes and discusses some recent initiatives aimed at securing biodiversity conservation on privately tenured rural land within Australia and overseas. First, we describe three schemes in Australia which represent a good sample – albeit not the entirety – of recent initiatives. Among other things, they demonstrate an ongoing shift in funding models. We evaluate some of the advantages and disadvantages of that shift. Second, we briefly describe some different schemes and programs in five overseas jurisdictions. Again, there is no attempt to be comprehensive. Our goal is to highlight some alternative approaches that may be of interest to Australian readers and to indicate additional resources that cover these schemes in more detail. We recognise that the Australian situation – environmentally, legally and politically – is different from those of the selected countries, but this does not mean they have no lessons for us. Some potentially relevant lessons are identified in the Discussion.

Biodiversity Conservation in Australia – the Context

Biodiversity decline is a common outcome of humans' transformation of landscapes to support their food and fibre production, infrastructure, mining, lifestyles and urban settlements (IPBES, 2022). There is increasing evidence, however, that biodiversity loss is detrimental to ecosystem services – such as clean air and water, nutrient and water recycling, and climate stability – and it reduces our resilience to extreme weather events (IUCN, 2022; IPBES, 2022). The gravity of this dilemma was recognised by the international community when it adopted the Convention on Biological Diversity in 1993. Unfortunately, neither that measure nor those of individual nations since then have been able to prevent continuing biodiversity decline. In 2022, the Intergovernmental Panel on Climate Change warned that ongoing global warming, including increases in the number and intensity of extreme natural events, will exacerbate the continuing loss of biodiversity (Portner et al., 2022). The IPCC assessment suggests that the conservation, protection and restoration of ecosystems, including forests, will require adaptive measures developed and implemented with local communities and Indigenous people involved (Portner et al., 2022). It asserts that safeguarding biodiversity is fundamental to climate-resilient development (Portner et al., 2022).

The value of biodiversity for Australia, its continuing decline and its causes have been well documented (Cocks, 1992; Department of the Environment, Sport and Territories, 1993; Creswell & Murphy, 2016). Australia is unique because of its mega biodiversity and globally significant ecosystems (Creswell & Murphy, 2016). Australia has 12 World Heritage Sites based on natural values. We have several global biodiversity hotspots (very biologically rich regions with heavy native vegetation losses) including south-west Western Australia, the temperate forests of eastern Australia and Queensland's tropical rain forests (Creswell & Murphy, 2016).

The Australian Government has long recognised the need to reduce the adverse environmental impacts of land use change (Hawke, 1989; COAG, 1999). From 1982 onwards, state governments enacted legislation to stem the rate of vegetation clearing for agricultural purposes (Bates, 2019). This approach often generated a hostile response from landholders (Productivity Commission, 2004). Over time, the strength of the regulatory requirements has waxed and waned in the hands of governments of different political persuasions (England, 2016; Bates, 2019). Overall, legislation has had some success at stemming the tide of land clearing, but our rates of biodiversity loss remain concerning (Department of Agriculture, Water and the Environment, 2016; Department of Climate Change, Energy, the Environment and Water, 2021).

Land use change contributes to the spread of pest animals and weeds, which are a major contributor to biodiversity (and economic) loss (Steffen, 2009; Department of Agriculture, Water and the Environment, 2016; Shepard, 2021). The vulnerability of Australia's biodiversity to the impacts of invasive species benefiting from climate change is likely to exceed the direct impacts of climate change (Steffen, 2009; Corey, 2021; Shepard, 2021). The connection between biodiversity loss and economic loss has been well known to landholders and governments for many years (Sindel, 2000).

The majority of Australian land is owned and managed by private interests or government entities, such as Defence, some of which may not be under the direct control of government (Australian Trade and Investment Commission, 2022). Indigenous Peoples (Aboriginal and Torres Strait Islanders) are a significant landholding group. As of 2020, 17% of Australia was Indigenous owned and 57% of Australian land was either owned, managed, co-managed or subject to special Indigenous rights (Jacobson et al., 2020). Some particular programs, such as the Indigenous Rangers Program and savanna burning projects financed by the Climate Solutions Fund, have been carefully crafted to meet the interests of these stakeholders and appear to be meeting with success (National Indigenous Australians Agency, 2022). Nevertheless, 55% of the Australian land mass is used for agriculture, so measures that are designed to sit alongside and operate specifically in the context of agricultural activities are also vitally important (ABARES, 2022). Agricultural landholders will continue to have a major impact on the success or failure of biodiversity conservation measures (Taylor, 2012; Bourke, 2012; Whitten, 2016). This article is focused on schemes which address this community in particular.

Schemes for Securing Biodiversity Conservation in Australia – Three Examples

In this section, we survey three recent initiatives by different Australian governments – Queensland, New South Wales (NSW) and the Commonwealth. The first two initiatives, the Queensland Private Protected Areas Program and the New South Wales Biodiversity Offsets Program, illustrate, among other things, different approaches to funding biodiversity initiatives. The New South Wales scheme is significantly more complex, so we have chosen to describe and explain the funding arrangements for this scheme in some detail. The third scheme we describe is the Commonwealth's Emissions Reduction Fund. Although this scheme is not primarily a scheme to promote biodiversity conservation, we show how it is evolving to include that goal in conjunction with reducing carbon emissions. The Commonwealth scheme is our biggest experiment to date with tapping into markets for environmental management services. For this reason, we felt the scheme was worthy of some analysis in this article.

Queensland's Private Protected Area Program

In Queensland, the government runs a Private Protected Area Program to complement its system of public protected areas. This program encourages private landholders to partner with the state to protect conservation values on their land (State of Queensland, 2020). The operative mechanism is through the declaration of a nature refuge or, more recently, a special wildlife reserve. These two categories of privately held protected area extend across 4.47 million hectares – approximately 31% of Queensland's total protected area network (State of Queensland, 2020, p. 6). With 534 nature refuges in place, Queensland's Nature Refuge Program is now the largest private protected area program in Australia (Bowman, 2020; State of Queensland, 2020). Another indicator of their significance is that 6% of Queensland's regional ecosystems are found only on nature refuges (State of Queensland, 2020, p. 6).

In Queensland, establishing a nature refuge is generally a government-led initiative limited to sites which meet one or more selection criteria such as providing habitat for threatened species or ecosystems or establishing landscape linkages and corridors at a landscape level (State of Queensland, 2022).

The Department of Environment and Science (DES) has primary responsibility for identifying suitable sites and inviting relevant landholders to voluntarily participate in the program. Some aspects of the program seem relatively onerous. For instance, landholders must be willing to place the selected land under a permanent conservation covenant and negotiate a conservation agreement establishing a nature refuge in line with the relevant provisions of the *Nature Conservation Act 1992*. The conservation agreement will identify management actions the landholder must undertake to protect significant conservation values on the land (State of Queensland, 2021a).

There are two funding programs available to support nature refuges, but neither guarantees financial support to landholders. Under the Nature Assist Program, the Department may fund and manage contractors to complete identified conservation projects involving, for example, fencing to manage stock access; or constructing artificial watering points away from natural watercourses (State of Queensland, 2021a). Additionally, subject to available finance, landholders may apply for funding from the Nature Refuge Landholder Grants scheme to complete relevant projects themselves. Routine management actions, however, will not be funded by either scheme (State of Queensland, 2021b).

Despite their seemingly onerous nature, there is a growing level of interest in nature refuges: 57 new nature refuges, involving 479,190 hectares of land, have been declared since February 2015 (State of Queensland, 2020). Funding levels, however, do not seem to have matched their recent growth. A 2019 independent expert report, commissioned by a group of not-for-profit organisations, echoed concerns raised by landholders (Outback Alliance, 2019, pp. 3, 9):

> Funding for private protected areas is stretched to breaking point, with landholders receiving less than 25 cents per hectare over the past five years …
>
> The current level of support available to nature refuge landholders is insufficient to support landholders' efforts to effectively manage existing nature refuges or to provide an appropriate incentive for new entrants to the program. (Outback Alliance, 2019, pp. 3, 9)

The report recommended investing $24 million per year in new and existing private protected areas and drew attention to the New South Wales Government's budget allocation – of $247 million over four years – to support private landholders to protect and conserve natural values on their land (Outback Alliance, 2019). Encouragingly, in June 2022 the Queensland Government announced a $262.5 million investment program (over four years) to grow the state's network of national parks and protected areas (Department of Environment and Science, 2022). It remains unclear how much (if any) of this money will be directed towards delivering a better deal for landholders managing existing private protected areas.

NSW Biodiversity Offsets Program

In New South Wales, biodiversity stewardship agreements have been linked to the state's Biodiversity Offsets Scheme since 2016 (State of New South Wales (Department of Planning and Environment), 2022a). This scheme applies when new development projects will cause significant adverse environmental impacts despite preventive and mitigating measures (State of New South Wales (Department of Planning and Environment), 2022a). It requires developers to fund or provide environmental offsets to compensate for the residual adverse impacts caused by their development (State of New South Wales (Department of Planning, Industry and Environment), 2022b). Environmental offsets are any measures that generate conservation outcomes that are not otherwise secured (Bates, 2019). The specific goal of biodiversity offsets is "to achieve no net loss and preferably a net gain of biodiversity on the ground with respect to species composition, habitat structure, ecosystem function and people's use and cultural values associated with biodiversity" (Business and Biodiversity Offsets Program, 2009, p. 4).

In New South Wales, the *Biodiversity Conservation Act 2016* provides the current framework for linking developers, who have been approved to clear or develop land subject to offset conditions, with landholders, who are in a position to provide for and maintain environmental values in accordance with a Biodiversity Stewardship Agreement (Bates, 2019; State of New South Wales (Biodiversity Conservation Trust), 2022a). Similar to a nature refuge conservation agreement in Queensland, a Biodiversity Stewardship Agreement (BSA) is a voluntary agreement between the Biodiversity Conservation Trust and a landholder to permanently protect and manage an area of land (State of New South Wales (Biodiversity Conservation Trust), 2022a). However, unlike their Queensland counterparts, a biodiversity stewardship agreement generates biodiversity credits which may be sold to a developer, the Biodiversity Conservation Trust or other interested parties (State of New South Wales (Biodiversity Conservation Trust), 2022a).

The Biodiversity Offsets Scheme embraces some complex terminology but operates generally in this way. Approvals for clearing or developing land are routinely granted by statutory planning authorities subject to conditions. If the approved clearing or development will cause significant environmental impacts which cannot be avoided or adequately mitigated, the developer will be required to provide an offset to compensate for those impacts (Bates, 2019; State of New South Wales (Department of Planning and Environment), 2022b). This obligation takes the form of a credit obligation which must be retired before the activity can commence (State of New South Wales (Department of Planning and Environment), 2022b). One way developers can retire their credit obligation is by purchasing biodiversity credits from landholders who have a Biodiversity Stewardship Agreement in place on their land (State of New South Wales (Department of Planning and Environment), 2022b; Bates, 2019). A Biodiversity Stewardship Agreement (BSA) is a contract made between a landholder and the Biodiversity Conservation Trust (the Trust) which is the statutory body appointed to administer the Biodiversity Offsets Scheme (State of New South Wales (Biodiversity Conservation Trust), 2022b). To obtain a BSA, landholders must offer land – a Biodiversity Stewardship Site – which meets the eligibility criteria (State of New South Wales (Department of Planning and Environment), 2022c). Landholders will need to retain an accredited assessor to apply the Biodiversity Assessment Method to the site (State of New South Wales (Department of Planning and Environment), 2022c). The assessor will produce a Biodiversity Stewardship Site Assessment Report identifying the type and number of biodiversity credits that will be generated by placing a BSA on the site (Bates, 2019; State of New South Wales (Department of Planning and Environment), 2022c). It will also identify and cost annual maintenance activities over a 20-year period. These costs constitute the Total Fund Deposit (State of New South Wales (Department of Planning and Environment), 2022c).

Once the BSA is formalised, the agreement and credits will be registered, including on the title to land (State of New South Wales (Department of Planning and Environment), 2022c). Landholders can then sell their biodiversity credits either to the Trust (for on-selling to developers); directly to a developer who will use those credits to retire its credit obligations; or to any other interested purchaser – e.g. government bodies or philanthropic organisations (State of New South Wales (Department of Planning and Environment), 2022c). The developer and landholder are free to negotiate a price, but it must at least cover the cost of the Total Fund Deposit (State of New South Wales (Department of Planning and Environment), 2022c). When the biodiversity credits are sold, a landholder must transfer the Total Fund Deposit to the Trust's Stewardship Payments Fund. The Trust will then make an annual payment to the landholder to maintain the Biodiversity Stewardship Site in accordance with the management plan (State of New South Wales (Department of Planning and Environment), 2022c).

Although the Biodiversity Offsets Scheme is organised around a marketplace that directly links buyers (developers with credit obligations) and sellers (landholders in possession of biodiversity credits), the Biodiversity Conservation Trust, a publicly funded statutory body, also has a crucial role to play. For instance, it enters into BSAs with landholders; it manages the Biodiversity Stewardship Payments Fund from which landholders receive their annual management payments; and it ensures landholders are complying with their management commitments (State of New South Wales (Biodiversity Conservation Trust), 2022a). The Trust is charged with ensuring a steady supply of biodiversity credits is available to developers (State of New South Wales (Biodiversity Conservation Trust), 2022a). It is subject to the control and direction of the Minister for Energy and Environment, except in relation to payments from the Biodiversity Conservation Trust Public Fund (State of New South Wales (Biodiversity Conservation Trust), 2022b).

The original NSW Biodiversity Offsets Scheme was revised in 2016 and this seems to have led to a reinvigorated program. Up to July 2014, only 29 bio-banking agreements (previous scheme terminology) had been approved and 5000 hectares of native vegetation set aside (Bates, 2016). As of 2022, over 195,000 hectares of land are protected by private land conservation agreements, including BSAs, and 368 landholders have signed or are in the process of signing conservation agreements (State of New South Wales (Biodiversity Conservation Trust), 2022c).

Aside from the Biodiversity Offsets Scheme, the Trust delivers additional conservation programs on private land in accordance with the NSW Biodiversity Conservation Investment Strategy 2018 (State of New South Wales (Biodiversity Conservation Trust), 2022d). A budget of $350 million (over a five-year period) has been allocated to the Trust's private land conservation programs (State of New South Wales (Biodiversity Conservation Trust), 2022d).

The NSW Biodiversity Offsets Scheme is a proactive and relatively well-funded initiative that supports not only the establishment of permanent reserves on privately held land but also the ongoing provision of finance, support and monitoring in relation to their maintenance and upkeep – in contrast to the Queensland Protected Areas Program. The scheme also benefits from the support of a dedicated statutory agency driving the program. Nevertheless, a recent review of the scheme's effectiveness identified a number of unresolved flaws in the scheme (NSW Auditor-General, 2022). In particular:

- there is no clear strategy to ensure its work is consistent with the *Biodiversity Conservation Act 2016*;
- there is a shortage of available biodiversity credits, and those that are available are poorly matched to growing demand; and
- key concerns around the scheme's integrity, transparency and sustainability remain unresolved (NSW Auditor-General, 2022).

Overall, the report concludes: "[T]here is a risk that biodiversity gains made through the Scheme will not be sufficient to offset losses resulting from the impacts of development, and that DPE [Department of Planning and Environment] will not be able to assess the Scheme's overall effectiveness" (NSW Auditor-General, 2022, p. 2).

Many of the weaknesses of the NSW scheme identified in the Auditor-General's report are mirrored in the academic literature on environmental offset schemes generally (Gibbons & Lindenmayer, 2007; Maron et al., 2012; Maron & Gordon, 2013; Norris, 2014; Falding, 2014; Bates, 2016; Dwyer, 2016). The timing, quality, comparability and reliable delivery of offsets are common issues that bedevil offset schemes (Falding, 2014; Norris 2014; Dwyer, 2016). There seem to be few examples of good environmental outcomes emanating from these schemes to date (Maron, 2012; Maron & Gordon, 2013). There is also the fear that developers (and decision makers) will resort to offsets too readily instead of insisting on costly mitigation measures or rejecting outright development that will cause unacceptably high environmental impacts (Gibbons & Lindenmayer, 2007). These concerns are mirrored at the international level: the 2021 IPBES-IPCC report found that only about one third of 12,983 cases in 37 countries demonstrably deliver 'no net loss' outcomes (Portner et al., 2012).

The Emissions Reduction Fund and Carbon + Biodiversity Pilot

The Emissions Reduction Fund is the main scheme for funding voluntary measures to reduce the nation's greenhouse gas emissions. In this scheme, proponents of eligible projects registered with the Clean Energy Regulator bid for funding from the government in quarterly auctions. Eligible projects must satisfy one of the approved methodologies for reducing emissions, including requirements about newness and regulatory additionality (Clean Energy Regulator, Commonwealth of Australia, 2020a). Contracts are awarded to proponents offering the lowest price for their emissions reductions (the 'reverse auction'). For each successful proponent, the government purchases Australian carbon credit units (ACCUs) and transfers them to the project proponent once the project is completed. The proponent may then choose to sell their ACCUs back to the government or in the secondary market (Clean Energy Regulator, Commonwealth of Australia, 2022b).

Although biodiversity protection is not the main focus of the Emissions Reduction Fund, some of the adopted methodologies seem to lend themselves to complementary biodiversity outcomes. For instance, eligible projects include: "environmental or mallee plantings; avoided clearing of native regrowth (subject to newness and additionality requirements); avoided deforestation; native forest from managed regrowth; reforestation and afforestation. Agricultural projects are also eligible – including soil carbon and higher quality pasture for cattle – and so too are savannah fire management schemes" (Clean Energy Regulator, Commonwealth of Australia, 2022a). As of 2019, the Clean Energy Regulator had registered more than 780 projects and purchased over 192 million tonnes of abatement (Clean Energy Regulator, Commonwealth of Australia, 2020b).

Despite the apparent complementarity of sequestration and biodiversity objectives, concerns have been expressed that not all projects funded by the CSF/ERF have promoted biodiversity (Blakers & Considine, 2016; Reside et al., 2017; Corey et al., 2020; Standish & Prober, 2020). The priority afforded to carbon sequestration precludes a more holistic treatment (Reside et al., 2017). In a bigger debate, critiques have also been made regarding the overall integrity and actual emissions reductions attributable to the scheme (Commonwealth of Australia (Climate Change Authority), 2020; Crowe, 2020; MacIntosh, 2022; Hemming et al., 2022).

The Agriculture Biodiversity Stewardship package, a more recent initiative commenced by the previous government, includes funding for a Carbon + Biodiversity Pilot to strengthen the biodiversity credentials of the Emissions Reduction Fund. In this pilot project, farmers who undertake new vegetation plantings for carbon abatement will be eligible for additional payments if they plant a mix of species and manage the vegetation to realise biodiversity benefits in conjunction with carbon abatement (Department of Agriculture, Water and the Environment, 2022a). Other features to be developed and included within the Agriculture Biodiversity Stewardship Scheme are an Australian Farm Biodiversity Certification Scheme and a Biodiversity Trading Platform (Australian Farm Institute, 2020). Whilst the new program aims to reward farmers for delivering biodiversity outcomes, the linkage with, and dependence on, funding from the Climate Solutions Fund may continue to constrain the realisation of biodiversity goals. For instance, the Pilot project is focused on new environmental plantings with a mix of two or more species rather than on protecting and enhancing mature, ecologically complex vegetation already in existence (Department of Agriculture, Water and the Environment, 2022b). A similar scheme in Queensland, the Land Restoration Fund, has been criticised by industry groups as poor value for money (Moore, 2020).

Some Overseas Comparisons

Here, we describe some conservation initiatives in North America, the United Kingdom, the European Union, China and Costa Rica. The schemes under review include but are often not limited to securing land for biodiversity conservation. A comprehensive and detailed survey of measures in each of these jurisdictions is beyond the scope of this article. Rather, the authors have chosen here to select and briefly describe measures which suggest alternative or varied approaches to those in Australia. Our purpose is to encourage readers to think broadly about additional measures that could usefully supplement the range of mechanisms currently in operation in Australia.

North America

The United States (US) *Agriculture Improvement (Farm) Act of 2018* (with updated provisions in 2021) authorises several programs to address the conservation of biodiversity (see Title 11, Programs on Stewardship and Reserve, and Soil Health). These include: an Environmental Quality Incentives Program; a Conservation Stewardship Program; the Regional Conservation Partnership Program; the Conservation Reserve Program (CRP); the Working Lands for Wildlife Program (which targets conservation and enhancement of wildlife and endangered species habitat); the Agricultural Conservation Easement Program (which targets specific issues such as wetlands management); and the Conservation Technical Assistance Program (which provides private landowners and organisations with technical expertise to guide sound natural resource management decisions) (USDA, 2018). Funding for these programs, administered by the US Department of Agriculture (USDA), is substantial – approximately AU$10 billion per annum (USDA Natural Resources and Conservation Service, 2021a).

The Conservation Reserve Program is, in essence, a government land rental scheme which takes private land out of production through a reverse auction mechanism, thus removing from the market the goods that land would have produced and paying instead for land restoration (Mandle et al., 2019; USDA Farm Service Agency, 2021). Contracts are for an initial period of 10 to 15 years with options to continue the annual payments. The bids to change land management are assessed against a set of criteria covering benefits to wildlife habitat, water quality and reduced erosion, run-off and leaching, and air quality benefits from reduced wind erosion, all of which are likely to endure beyond the contract period. Another subprogram covers Grassland Enrolment. Land can be offered for Continuous Enrolment at any time without competitive bidding. The USDA estimates the CRP has prevented over 8 billion tonnes of soil from eroding and restored 275,000 km of streams with riparian buffer strips (USDA Farm Service Agency, 2021). The US Government is aiming to increase the extent of the Conservation Reserve Program (CRP) from 24 million acres to 27 million acres (9.7 million ha to 12 million ha) by 2023 (USDA, 2018).

In the Regional Conservation Partnership Program (RCPP), activities must be undertaken as partnerships between stakeholders – including not-for-profit organisations, land trusts, landowners, and other groups who provide matching funds including in-kind services such as monitoring, conservation planning and producer assistance. RCPP projects address natural resource management at a landscape level (USDA, 2022b). This includes identifying and managing Critical Conservation Areas such as the Prairie Grasslands Region which extends across 11 states. Management measures address a range of issues including: degraded plant condition; excess water/flooding; inadequate habitat; and insufficient water/drought (USDA, 2022b).

Two examples demonstrate the scope of the RCPP. The American Prairie Reserve, based in Montana, connects 1.2 million hectares of public lands with purchases since 2004 of 175,000 hectares of private lands. The aim is to create a seamless and fully functioning ecosystem including wildlife corridors (American Prairie Foundation, 2021). The project was initiated after an assessment in 1999 by The Nature Conservancy of the need for eco-regional planning for the Northern Great Plains Steppe. A not-for-profit organisation, the American Prairie Foundation, was established in 2001. As of 2019, the Foundation holds assets worth US$101.3 million. Scientific support has been critical to the success of the Foundation, and it continues to benefit from the input of an 11-member Scientific Advisory Council.

The Saskatchewan Prairie Conservation Action Plan was established in 1998 (Saskatchewan Prairie Conservation Action Plan, 2021). It focuses on Native Prairie Education and Awareness, Responsible Land Use and Ecosystem Management. Since 2011, it has hosted workshops on restoration, reclamation and development, bringing together more than 1500 participants over six events. The Action Plan operates as a partnership of 31 Partners: multisector government agencies (Federal, Provincial, Local and Indigenous); industry; NGOs; and private agencies. Each Partner organisation has a representative that participates in the Steering Committee which meets three times per year. An Executive Committee, made up of the chair and four to five Partner representatives, has oversight of business and operational matters. A full-time manager, part-time Education Coordinator, Stewardship Coordinator and technical support maintain the organisation's communication and programming, operating out of the Saskatchewan Stock Growers' Association Office (Saskatchewan Prairie Conservation Action Plan, 2021).

United Kingdom

While the United Kingdom (UK) was a member state of the European Union (EU), its landowners received payments under a government Basic Payment Scheme and from EU-funded subsidies. These subsidies typically made up over 50% of farmers' incomes and, until recently, were not targeted at delivering ecosystem services. In the aftermath of Brexit, a new scheme is commencing. The *Agriculture Act 2020* provides the legislative framework for these changes (Tsouvalis & Little, 2020).

The new scheme will shift payments away from a per-hectare basis in favour of payments for producing and maintaining public goods – in this case, environmental services. Over the next seven years, 82,500 farmers will be engaged in environmental land management contracts. The process involves an initial mapping exercise identifying areas best suited for agriculture and those best suited for producing ecosystem services.

Payments from the scheme will operate on three tiers (Harris, 2020). Tier 1 will "encourage farmers to adopt environmentally sustainable farming and forestry practices" (Harris, 2020). In this tier, farmers will "be paid for taking action rather than delivering outcomes" (Harris, 2020). Tier 2 will "encourage farmers, foresters and land managers with specialist knowledge, to deliver locally targeted environmental outcomes" (Harris, 2020). Payments will be made for specific "services such as tree planting, flood mitigation, habitat creation, restoration or management" (Harris, 2020). Tier 3 payments will be made to "farmers and land managers who undertake transformational landscape-scale projects" such as restoring major soil degradation (Harris, 2020).

In addition to this emerging new scheme, the government also funds farmers who wish to take part in the UK Countryside Stewardship Scheme. This scheme was established in 1991 and now covers 530,000 hectares at a per-annum cost of UK£52 million (ca. AU$94 million). The scheme aims at sustaining the beauty and diversity of the rural landscape and providing wildlife habitat. Participants are contracted over a 10-year period to deliver agreed land uses such as arable land conversion, maintaining grassland and making provision for wildlife habitat.

Somewhat analogous to the Australian Commonwealth's Climate Solutions Fund, the UK has also developed a system for reverse auction projects funded by private water companies (Peacock, 2017). In this scheme, farmers undertake agreed action to protect or improve the quality of the public water supply (Peacock, 2017). Because the outcomes are visible infrastructure or land management changes, the projects are easy to manage, and the success of the pilot projects suggests that more will follow (Peacock, 2017).

Underpinning many of these developments is the influential Dasgupta Review of 2021 (Dasgupta, 2021). This landmark report placed biodiversity at the core of economics and argued the economic case for an urgent response to biodiversity loss and decline. The British Government reacted positively to this analysis and, in response, embraced a general commitment to leave the environment in a better state than we find it and to ensure that collective demands on it are sustainable (Badenoch, 2021). It also announced a species abundance target and an increase in protected land and sea programs (Badenoch, 2021). It has adopted an ambitious Ten Point Plan for a green industrial revolution mobilising "£12 billion of government investment…. to create and support up to 250,000 highly skilled green jobs" across the UK (HM Government, 2020; Badenoch, 2021, p. 2).

European Union

Since 1962, rural communities in the EU have been subsidised through the Common Agricultural Policy (CAP), a scheme worth approximately 38% of the EU budget (about €54 billion per year since 2006). In the past, CAP subsidies often contributed to environmental damage with little broader social benefit beyond farming, but the scheme has evolved over time. Initially offering price support to increase production (Pillar 1), it now provides direct payments for keeping land out of production for at least five years (Pillar 2 payments) and support for securing environmental sustainability goals. Subsidies are being re-directed into support payments for farmers who implement environment and climate-friendly practices, as outlined in the UN Sustainable Development Goals 2030, the Green New Deal and Green COVID-19 recovery (Scown et al., 2019).

Less well known than the CAP is the EU's LIFE Program. This program started in 1992 and is the key funding instrument for nature conservation and biodiversity health in the EU. It leverages national and other co-funding. LIFE funds support another major EU initiative, Natura 2000. Since 1992, Natura 2000 has created a continent-wide ecological network of protected areas across 28 countries, protecting 1500 animal and plant species and 200 habitat types. Natura covers 28,000 sites across 1.35 million km^2, 18% of the EU's total land area. The LIFE program has funded strategic land purchases of more than 200,000 hectares and extended the area covered under land management agreements on private land (EU, 2020). The proposed budget for LIFE in 2021 is €5.4 billion per annum. The LIFE program claims to have demonstrated the social and economic benefits that nature provides and changed attitudes towards nature conservation within the EU citizenry (EC, 2022).

In addition to the LIFE program, in 2019 the EU instituted the European Green Deal (EC, 2022). This aims to preserve and restore Europe's natural capital in accordance with the EU Biodiversity Strategy for 2030. It receives funding from member countries in the order of €20 billion per year. The goal is to extend legally protected areas in Europe to at least 30% of land area (134 million hectares) including trans-European ecological corridors.[a]

China

Over the past decade, China has embarked on a massive 'National Program to enhance environmental services and thereby create an Ecological Civilization' through a four-step program which entails:

(a) conducting a national ecosystem survey and assessment; mapping ecosystems and identifying crucial areas requiring ecosystem service provision;
(b) evaluating how to most effectively secure the required ecosystem services; and
(c) translating all this into practical and effective policies, including:
  - zoning by ecological functions;
  - developing compensation method(s) for ecological services provision, including novel systems of payments for ecological services (PES) on a large scale;
  - implementing ecological restoration methods;
  - establishing a sustainable supply of ecosystem services as a national goal; and
  - developing Gross Ecosystem Product (GEP) accounting.

The adopted approach first identified the ecological problem and relevant land restoration science and then assessed and developed ways to provide the required ecosystem services (Ouyang et al., 2016; Ouyang et al., 2019). The aim is to make the provision of ecosystem services a major component of environmental management with policies and financial mechanisms to back this up (Boer et al., 2020).

During the initial data collection phase, information was assembled on food production, carbon sequestration, soil retention, sandstorm prevention, water retention, flood mitigation, and habitat for biodiversity. Sixty-three Key Ecological Function Zones (KEFZs) were identified, covering 4.74 million km^2. These zones provide 60–80% of the major ecosystem services. The exercise also provided the basis for Ecological Asset Accounting and natural capital assessment for Eco-compensation.

Ecological compensation policies were enacted to help communities transition towards new livelihoods and to promote land conservation. Transfer payments amounted to US$43 billion by 2019, with $US9 billion distributed across 700 counties in 2017. The amount received by individual farmers is determined at the local level. The funds support national nature reserves and national park planning, ecological restoration projects and recruitment, training and salaries of rangers to protect KEFZs, as well as pollution reduction and mitigation measures.

The Sloping Land Conversion Program was established to control soil erosion and dust storms by taking vulnerable land out of grain production and converting it to horticulture and forestry, tree and grassland production. The scheme is one of the largest PES programs in the world, with the participation of 124 million farmers and, by 2013, reforestation of 31.8 million hectares of vulnerable land. The outcomes are mixed, suggesting that some ecological states of natural capital may not be restorable. Nevertheless, the claimed benefits are: a decline in soil erosion and surface run-off by 30%; a 22% reduction in siltation in the Yangtze and Yellow River Basins; and a reduction in dust storms and in wind speeds at the soil surface (Ouyang et al., 2019).

Costa Rica

On the international stage, a 'debt for nature swap' involves developed country institutions forgiving commercial or bilateral debt held by developing countries on condition an equivalent amount of some or all of that value is made available within the developing country for use in environment rehabilitation projects as long-term bonds or a specific fiscal budgetary item. Debt for nature swaps first commenced in 1988 (UNDP, 2017) and have been used more extensively in Costa Rica than in any other country.

[a] By way of comparison, the Queensland Rangeland area covers approximately 150 million hectares.

Until the 1990s, Costa Rica was known both for its outstanding biodiversity and record high deforestation rate. From that time onwards, recognition of the intrinsic value of its natural capital has led to an ambitious and novel system of payments for environmental services (PES) based on debt for nature swaps. The focus is twofold: on improving and expanding the National Parks system; and on incentivising 200 private conservation reserves with payments for environmental services. There is a focus on forest protection, commercial reforestation, agroforestry, and regeneration in degraded areas. The basic payment for forest protection is US$64/ha/year over a 5-year period, with indigenous communities making up 10% of the beneficiaries. Net reforestation is now occurring, with 27% of the land area under protected status and a further 20% (over 1 million hectares) placed under PES programs which incentivise conservation.

Over the last 30 years, the scheme has reversed deforestation in Costa Rica. The nation now has more than 50% of its land under some sort of forest cover, up from less than 30% when the policies around land use changed in the late 1980s. The PES schemes have evolved over time, along with a significant cultural change. While the complementary programs have secured the environment, they are also noticeable for improving the livelihoods of rural and indigenous peoples (Quesda, 2019).

Costa Rica has led the way in governmental recognition of the need to halt deforestation. It has elicited financial support through debt for nature swaps involving both commercial and bilateral debt, complemented by interactions with private donors, international and national NGOs, international agencies such as the World Bank and Global Environment Fund, and bilateral funding. The key to its success seems to be the strong level of commitment by the government and the community in recognising the significance of deforestation and the importance of restoration activities, making Costa Rica's success internationally known. Whilst it is unlikely commercial banks would allow debt for nature swaps in the Australian context, a plausible option could be for the government to fund debt write-offs in return for nature conservation activities.

Discussion

The first part of this article surveyed three schemes supporting biodiversity outcomes in Australia. Although not by any means a comprehensive survey of schemes and initiatives across Australia, the schemes surveyed illustrate three emerging trends:

1. There Is Growing Interest in Conservation Initiatives on Privately Held Land

This trend has been evolving since the 1980s when, for example, controls on the clearing of native vegetation on private land were first mooted (Bates, 2019). Queensland's protected area program, which was originally one of the measures accompanying vegetation clearing controls in that state, is a good example of the scale and significance this trend has now reached. Privately held protected areas in that state account for approximately 31% of its total protected area network (State of Queensland, 2021a).

2. Biodiversity Conservation Is Becoming Increasingly Commodified

The New South Wales Biodiversity Offsets Scheme, the Climate Solutions Fund and the Carbon + Biodiversity Pilot exemplify this trend. This trend potentially opens doors to significant new sources of funding from private investors seeking to offset their development impacts and reduce their carbon emissions profiles. The allure for cash-strapped state and federal governments is self-evident (Carbon Farming Institute, 2017). Three observations, however, provide an important caveat on the apparent opportunities. First, there is ample evidence that offset schemes in general do little to stem the tide of development-led environmental degradation and may even encourage it (Gibbons & Lindenmayer, 2007). Second, developers and industry partners are often motivated by a mix of factors, meaning genuine biodiversity conservation will often play a secondary role to other factors such as the need to offset carbon emissions (Seddon, 2021). The existence of multiple motivations means biodiversity objectives may be compromised (Blakers & Considine, 2016; Reside et al., 2017; Corey et al., 2020; Standish & Prober, 2020). Third, despite increasing interest in these schemes from developers, the reality, for the time being, is that state and federal governments are the most significant investors in these programs. The generous budgetary support for the Biodiversity

Stewardship Trust from the NSW Government, as outlined in its Investment Roadmap, exemplifies this point (State of New South Wales (Biodiversity Conservation Trust), 2022d). Private markets on their own, it seems, are a long way from driving or even sustaining a credible response to our biodiversity investment needs (England, 2021). With significant public money being channelled into these hybrid public-private schemes, questions about value for money are and will remain pertinent (Blakers & Considine, 2016; Moore, 2020; Australia Institute, 2020). In recent months, the integrity, accountability and transparency of these schemes have been questioned (MacIntosh, 2022; NSW Auditor-General, 2022).

3. Biodiversity Conservation Is Becoming Increasingly 'Bundled' with Carbon Mitigation Measures

In Australia, the Carbon + Biodiversity Pilot illustrates this trend. This trend is also occurring overseas (Seddon, 2021). As noted above, the risk inherent in this bundling of seemingly compatible interests is that biodiversity outcomes will be compromised in favour of obtaining quick, substantial and easily verified carbon sequestration outcomes (Blakers & Considine, 2016; Standish & Prober, 2020; Seddon, 2021).

In the second part of this article, we surveyed a range of alternative approaches and programs for biodiversity conservation in jurisdictions outside Australia. There were some striking points of contrast between Australia and overseas.

Other Countries Are Investing Substantial Amounts of Government Funding in Conservation Projects

In the United Kingdom, for example, public sector expenditure on environment protection was £13.9 billion in 2021–2022, compared with £12.9 billion in the previous year. Compared with 1998–1999, environment protection spending increased by £7 billion in real terms (Clark, 2022). In North America, the USDA spends approximately AU$10 billion per annum funding environmental stewardship programs, reserves and soil health programs. In the European Union, the budget for the LIFE program alone amounts to approximately €5.4 billion per annum. A recognition that biodiversity and nature conservation are public goods that deserve much greater recognition and support than in the past seems widespread overseas. That recognition, and measures which flow from it, seem somewhat tokenistic in Australia by comparison (England, 2021).

Direct Payments to Landholders Are Mandated Part of Conservation Framework

These direct payments are not linked to, or contingent upon, market funding. Again, the United Kingdom provides a salient example. When the UK was a member of the European Union, landholders typically earned up to 50% of their income from EU-funded subsidies. That support mechanism is now being redirected into contracts for providing environmental services (Tsouvalis & Little, 2020; Harris, 2020). In North America, the Conservation Reserve Program engages individual landowners to take land out of production and to provide environmental services for that land instead.

An analogous approach to the Conservation Reserve Program in Australia would be for the government to contract with landholders to remove cattle, sheep or goats from their land and/or relinquish their leases, allowing the land to be re-designated as a protected area. In place of their production activities, the government would then pay landholders a regular wage to undertake land stewardship activities on the land. If there is a financial loan associated with the lease as the collateral asset, then negotiations with the bank(s) on ways to write this off or restructure – perhaps through a Rural Reconstruction and Development Bank (Katter, 2019) – would be needed at the individual farm level. Between 2007 and 2012, the Australian Government funded a similarly motivated Environmental Stewardship Program, with covenants and contingency funding for private land management commitments extending to 2024. The program operated as a reverse auction system, with private landowners bidding to improve habitat quality across the landscape with buffers for high-quality remnants of endangered species, ecological communities, Ramsar wetlands and World Heritage Sites. The program sought to create "enduring changes in attitudes and behaviours of land managers towards environmental protection and sustainable land management practices" (Burns et al., 2016, p. 36). Despite favourable independent reviews of the program, it was terminated by the Abbott Government in 2012.

Some Partnerships with Not-for-profit Organisations Harness Additional Funding

The Regional Conservation Partnership Program in North America, which operates on a landscape scale across 11 states, is an example of this phenomenon. It partners with a range of stakeholders who provide matching resources including in-kind services. Like North America, Australia is home to a number of well-established not-for-profit organisations engaged in the acquisition and management of land for conservation purposes (Cowell & Williams, 2006). From 1993 to 2014, public money was available to these organisations to assist them in the acquisition of land for conservation purposes. A review of the National Reserve System Programme in 2006 found that partnering with the not-for-profit sector was a highly efficient method of extending Australia's network of protected areas (Gilligan, 2006). The Gilligan Review recommended increasing investment in the Programme and for at least two-thirds of the costs of new partnership acquisitions to be borne by the Australian Government (Gilligan, 2006). The Programme stagnated, however, from 2014 when funding for it was merged with the National Landcare Program (Department of Agriculture, Water and the Environment, 2016).

Comprehensive and Ambitious Approach to Nature Conservation

In this respect, China's national program to enhance environmental services and thereby create an 'ecological civilization' appears exemplary in its breadth and rigour. The four-step program included a preliminary ecosystem survey and assessment on a nationwide basis, followed by mapping and identification of priority areas and needs. This has allowed for a comprehensive scheme of investment including, but not limited to, payments for ecosystems services.

China is not alone in taking a strategic, landscape-based approach in its planning for biodiversity conservation. In the European Union, the Natura 2000 initiative covers 18% of the Union's total land mass, covers 28,000 sites and has funded more than 200,000 hectares of strategic land purchases (EU, 2020).

Australia is pursuing its own national Comprehensive, Adequate and Representative (CAR) Reserve System, which rests on a strategic, bioregional framework (Department of Agriculture, Water and the Environment, 2022c). It also has a national biodiversity conservation strategy (Commonwealth of Australia, 2019). Nevertheless, outside the example of its national reserves, actual funding models for biodiversity conservation tend to favour site-specific projects over and above achieving long-lasting regional or catchment-wide outcomes (Whitten, 2016). This approach to funding initiatives is unlikely to safeguard our biodiversity on a scale sufficient to cope with the anticipated impacts of climate change or other global changes (Whitten, 2016). Overseas experience showcases the importance of comprehensive planning for biodiversity and ecosystem services and the need for significant public funding to be aligned with that strategy. Comprehensive evaluation and mapping of the current status of the ecosystem services provided by our natural capital should be at the core of a comprehensive management approach not limited to planning for nature reserves.

Greater Recognition Is Given to Range of Ecosystem Services Provided by Biodiversity Conservation

This recognition is consistent with the IUCN's Nature-based Solutions advocacy (IUCN, 2021). In the United Kingdom, some of the environmental co-benefits being recognised and supported include flood mitigation and land restoration (Harris, 2020). In China, the list of identified environmental co-benefits includes contributions to food production, carbon sequestration, soil retention, sandstorm prevention, water retention and flood mitigation, as well as providing habitat for biodiversity (Ouyang et al., 2016; Ouyang et al., 2019). In the European Union, climate mitigation goals are identified as desirable co-benefits of some biodiversity conservation programs; but, unlike Australia's Climate Solutions Fund, they are not driven primarily by the desire to offset carbon emissions (Scown et al., 2019).

Explicit Recognition of Biodiversity Contribution to Economic Well-being

In the United Kingdom, the government has accepted the findings of the influential Dasgupta Review that biodiversity underpins the whole economy, not just environmental well-being (Dasgupta, 2021). The government has now adopted an ambitious plan for a "[G]reen industrial revolution" underpinned by a £12 billion investment (Badenoch, 2021, p. 2). In an even more holistic approach, debt for nature swaps in Costa Rica have made an important contribution to improving the livelihoods and well-being of rural communities. The same understanding underpins the IUCN's position on Nature-based Solutions (IUCN, 2021). Despite calls from various actors for an environment-led recovery in the aftermath of COVID (The Greens, 2022; Farmers for Climate Action, 2001), the Australian Government seems yet to value the role biodiversity plays in contributing to a sustainable and resilient economic future (Australian Institute of Architects, 2021).

Conclusion

Australia has made some strides towards expanding the range and type of programs available to support biodiversity conservation on privately tenured rural land, but experience in other countries highlights that there are more options and some promising approaches with which Australia is yet to engage. Of particular instruction is the willingness of overseas governments to invest very significant sums of public money in biodiversity conservation without that investment being directly tied to commercially driven funding and/or carbon emissions-related objectives. The benefits of market-based and carbon-linked biodiversity conservation schemes have not yet been demonstrated, at least not in terms favourable to biodiversity conservation. Looking to international experience confirms our view that we should not be so hasty to 'put all our eggs in one basket'. We need increased domestic awareness of the importance of biodiversity and Nature-based Solutions generally, and increased public investment in direct, landscape-scale biodiversity conservation initiatives. We would also do well to explore an ongoing role for effective partnerships with a wide range of stakeholders, provided broader biodiversity conservation objectives will not be compromised. All of these matters, we believe, could usefully be encapsulated in a more expansive national strategy, delivering a level of coherence and ambition that is currently lacking in Australia.

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Coal, Bees and Fossils: The History and Significance of the Redbank Plains Formation Fossil Sites, South East Queensland

Alan Rix[1]

ABSTRACT

The Redbank Plains Formation, between Brisbane and Ipswich in South East Queensland, provides fossil evidence of the fauna and flora of the earliest part of the Cenozoic era, and is dated from the Paleogene Period, specifically the late Paleocene–early Eocene (66–55 Ma). These fossils have been collected and studied for over 120 years, but the conjunction of agriculture in the then-rural Redbank Plains district, and the mapping of the valuable Ipswich coalfields, led to their palaeontological significance being recognised and documented. Scientific study began in 1916 and has continued since, revealing some of the earliest evidence of modern Australian fauna and flora. However, the area's rich underground coal resources and a hunger for residential land in a rapidly developing urban corridor, has resulted in the loss of or threats to the fossil sites. One deposit has been given local government status as a Conservation Park and remains accessible for scientific study, but the lack of either national or state protection for such significant sites in Queensland and Australia imperils our national geological heritage and its scientific contribution.

Keywords: Cenozoic, Eocene, Ipswich coal measures, fossil fish, fossil insects

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Introduction

In Australia there is just one Formation from the Paleocene–Eocene (66–55 Ma) which contains fossilised plants, along with vertebrates and invertebrates. This is the Redbank Plains Formation of South East Queensland, situated approximately 35 km south-west of Brisbane. First reported by settlers in 1900, the fossils tell us much about the palaeoecology of south-eastern Queensland during the early Cenozoic, and offer some of the earliest evidence of modern Australian fauna and flora, including fish, reptiles, birds, insects and some Australian plant families. Accordingly, this Formation is acknowledged as an important element of Australia's national geological heritage (Australian Heritage Council, 2012).

When the first fossils were found over a century ago, Redbank Plains was part of an isolated rural bushland settlement far from the city. Investigation by scientists has been spasmodic: two major research publications in the first half of the 20th century drew attention to the sites, which were then largely forgotten for several decades. The 're-discovery' of the Formation and its scientific significance occurred amid nearby mining and extractive industry and in the shadow of urban development of new housing estates on what was considered 'vacant' bushland.

Today, however, the Redbank Plains Formation deposits reflect the fate of a world-class fossil site located in a peri-urban area under intense pressure from rapid housing and associated development.

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Only one small locality, at Redbank Plains, remains as a recognised and accessible outcrop of these strata, and its proximity to Brisbane means that suburban housing has now surrounded it (Figure 1).

FIGURE 1. Map of Redbank Plains, Dinmore and surrounding urban development, with the Redbank Plains and Dinmore outcrops marked in yellow. Map background created using the *Atlas of Living Australia* (https://www.ala.org.au/), reproduced here under a Creative Commons Attribution 3.0 Australia Licence.

This paper reviews the history of the discovery and scientific understanding of the Redbank Plains Formation fossil sites, their geological and palaeontological significance, and their place in Australia's geological heritage.

The Redbank Plains Formation: The Cenozoic Geological Setting

In the Paleocene-Eocene periods, Australia was still connected to East Antarctica as part of the late Gondwanan land mass, although the process of separation from Antarctica was already well under way (McLoughlin, 2001). At northern latitudes a warm, wet climate encouraged the growth of broad-leaved forests (Byrne et al., 2011), and a plethora of fishes, insects, mammals, birds and smaller amphibians and reptiles was present. A variety of these are represented in the Redbank Plains Formation fossil fauna and flora.

There are several Cenozoic basins in South East Queensland, with the Redbank Plains Formation being part of the Booval Basin (Jell, 2013). These basins appear to have been lacustrine environments, hosting a rich diversity of plant and animal life. The fossils of the Redbank Plains Formation, therefore, provide insight into the history of Australia's modern biota, prior to the widespread speciation and radiation of more dry-adapted taxa during the subsequent Miocene and Pliocene periods (Byrne et al., 2008).

The Booval Basin outcrops in two remnant areas, near Dinmore and Redbank Plains (Figure 1) and unconformably overlies the Triassic-Jurassic Ipswich Basin. *Geology of Queensland* describes the geology of the area as follows:

> ... The Booval Group consists of the Redbank Plains Formation and the conformably overlying Silkstone Formation ... The Redbank Plains Formation comprises claystone, sandstone and shale averaging 67 m thick and interpreted as fluvial to lacustrine. Surface exposures are subdued, but commonly comprise ferruginised mudstone nodules ... The Redbank Plains Formation is regarded as Paleocene-Eocene, with some authors preferring Eocene (Jell, 2013, p. 594).

The single accessible fossil-bearing remnant of the Redbank Plains Formation occurs in the Ipswich City suburb of Augustine Heights. It lies across two adjacent properties and covers approximately

15 hectares, with a eucalypt tree cover and patchy understorey of shrubs and grasses. There are no visible rock faces or impressive strata of layered sediments. The fossils are mainly impressions within an iron-rich mudstone, weathering out from the overlying soil across the site. Deeper excavation reveals layers of shale and fragmentary mudstone interspersed with clays. Several younger igneous intrusions have also produced a prolific scattering of trachyte fragments and silica-rich rocks. These latter were shaped and used by Indigenous peoples in the past as tools, remnants of which are still *in situ*.

The separate site at Dinmore (some 7 km distant) was a former clay quarry, mined since the early 1900s, and was well known for its plant impressions in shales and clays, along with some insects, but the shallow quarry has been filled in and the site is no longer available for study.

Geological Mapping of the Ipswich Coal Measures

Determining that the Redbank Plains Formation was Cenozoic in age took some years (Jones, 1927), underpinned by the Geological Survey of Queensland's (GSQ) intensive mapping of the Triassic coal deposits of the Ipswich area in the 1890s and following decades. The Ipswich coalfield was an important source of fuel for early Brisbane, and for the Queensland industrial and power sector until the 1970s. The GSQ therefore put great effort into investigating its extent and possible exploitation, including coal deposits under Redbank Plains (Denmead, 1955; Mengel & Carr, 1976; Murray, 2010; Whitmore, 1991).

The Assistant Government Geologist, Walter Cameron, completed the first comprehensive report on the Ipswich coalfield in 1899. While GSQ's initial mapping did not include Redbank Plains in the east, it did so in Cameron's later work on the Ipswich coal measures, which included a second report in 1907 and comprehensive maps which were published in 1923 (Cameron, 1899, 1907, 1923).

In discussing the geology of the Ipswich coalfields in 1907, Cameron (1907) made the following comments about what he designated the "Redbank Plains beds":

> About the farming district of Redbank Plains there occurs an area of fissile shales which are seen to lie with a more or less distinct unconformity on the coarse grits and sandstones of the Bundamba Beds. They can be traced all round the southern margin of the beds of volcanic rocks, which give the chocolate soil of the plains, and been sunk on in various shafts along Six-mile Creek and on the farms in the south-eastern corner of this district. They have afforded some fragmentary fish remains and remains of Dicotyledonous plants, which latter circumstance points to a probable identity with the supposed Cretaceous beds found about Darra and Wolston (Cameron, 1907, p. 17).

Ettingshausen (1895) had originally interpreted the nearby Darra Beds as Cretaceous, but both Skertchley (1908) and Marks (1910) concluded that the Darra Beds were "Tertiary", and by 1913 Cameron had altered his assessment of Redbank Plains to "Cretaceo-Tertiary". His investigations of the coal prospects in the Redbank Plains area were referred to in the GSQ Annual Report of 1913 and in an analysis of the Tertiary beds lying across some of the Ipswich coalfield (Cameron, 1913). In the latter he provided (p. 412) a map of the "tertiary mudstones, sandstones and basalts over the Ipswich Coalfield" and argued that the pre-Tertiary denudation of the coal seams was infilled by considerable depths of Tertiary strata, up to 460 feet in one bore at Bundamba. His 1923 mapping subsequently showed a "Tertiary System", in which he distinguished between the "Redbank Plains Series" and the overlying "Silkstone Series". More exploratory work on the Ipswich coalfield was conducted from the 1950s onwards, including core drilling to determine stratigraphy in the Redbank Plains area (Denmead, 1955). The impact of this on the future survival of the fossil deposits is discussed below.

Redbank Plains Fossil Discoveries: The Jones Bee Farm as the Type Locality

There is a rich cultural and social history associated with the Redbank Plains fossil site. The area had long been inhabited by Indigenous peoples and used by them for ceremony and stone tool making. Local tribes of the Yuggara and Ugarapul peoples inhabited the area until the late 1800s. An archaeological study in 1991 found three Indigenous sites and a few isolated artefact scatters within the Woogaroo and Opossum Creek catchment area (which includes the fossil zone) (Ipswich City Council, n.d.).

Following the foundation of the Moreton Bay penal colony in 1824 and Ipswich in 1827, Redbank Plains was settled by Europeans for farming from the mid-1800s. It was not until 1900 that fossils were discovered, from a well on a property near Six-Mile Creek, and soon thereafter by the family of Mr Lewis Jones from surface rocks on their property, from where they operated an apiary business.

The Jones family patriarch, Lewis Jones, had migrated from Wales in the 1860s, purchasing land at Redbank Plains in 1865, where he lived and successfully grew cotton and other crops, later extending into cattle. This type of farming activity was the economic basis of rural Redbank Plains, supported by the Ipswich-to-Brisbane railway which came to the village of Goodna, 4 miles (6.4 km) to the north, in 1874. Jones named his house and farm 'Pentwyn', after his Welsh birthplace. The family also built the neighbouring 'Oakleigh' homestead (which still stands), where son Henry (H. L. Jones) established his apiary hives, with a honey factory and sawmill in Goodna. The Mel Bonum Apiary was a very successful business, renowned in Australia and overseas for its quality, with a focus on breeding Ligurian queen bees, and over 500 hives for honey production (Anon., 1892, 1894a,b, 1925).

The Jones land at Redbank Plains comprised 300 acres (122 hectares), bounded on the eastern side by Woogaroo Creek and next to the road from Goodna (now Keidges Road). Newspaper reports of the period extolled the virtues of the prosperous farms in the area and the diversity of produce grown (Anon., 1883, 1890).

The Jones land happened, however, to be situated on slopes that constituted the only fossiliferous surface outcrop of what later became known as the 'fossil fish bed' of the Redbank Plains Formation, now recognised as the type locality of this Formation. Several lengthy press articles in the 1890s about the local farming make no mention of fossil finds, however. Instead, *The Queenslander* on 27 January 1883 (p. 152) did report about the Jones farm that "good coal was known to exist on this property, but has not yet been worked".

Early Fossil Finds

In its mapping operations, GSQ was keenly interested in the palaeontology of the Ipswich coalfield areas. Fossils were first reported officially from "Goodna" in GSQ's Annual Report of 1900, where the Assistant Government Geologist, Benjamin Dunstan, reported that fish and plant fossils were discovered "at the head of Goodna Creek, about three miles south of the Ipswich Railway line" (p. 192).

The head of the GSQ, William Rands, sent for identification two specimens of fish remains from "near Ipswich" to the Director of the Australian Museum in Sydney in April 1900 (Geological Survey of Queensland, 1899, p. 654), and the Minister for Mines was advised in December 1902 that, although they had a single specimen of fossil fish from "Goodna", it had not been described and "no definite age can be assigned" (Geological Survey of Queensland, 1902, p. 50).

As Acting Government Geologist in 1904, Dunstan visited the Ipswich "locality where fossil fish have recently been found" on 16 July, and H. L. Jones was reported in the *Queensland Times* of 12 April 1904 (p. 2) as having "an excellently-preserved specimen of a fossil fish found at Redbank Plains", which he donated to the Ipswich Technical College Museum. It was not until 1914, however, that Jones donated a specimen to the Queensland Museum (QM), registered as QMF612. This was the first Redbank Plains fossil acquired by the Museum.

From that time onwards, reports and collections became more frequent. Staff from the Museum collected chelonian, fish and ostracod material in 1916, while in 1922 the geologist F. W. Whitehouse donated to the QM "remains of fossil fishes found in lenticular patches of iron-stained material in oil-shale deposits in H.L. Jones' property" (QM Archives, Donor Schedule 12 June 1922).

An additional reason that the Redbank Plains fossils became well known from this time was that the Jones family were active members of Ipswich society and regularly hosted visitors to their farm, including identities such as Sir Arthur Conan Doyle (Doyle, 1921). "Music, tennis, horses, mangoes, the bush and the bees were all magnets that attracted people to 'Oakleigh' from afar ...

Henry Jones's daughter Queenie recalled 'This was before the day of the motor car, but we always had company. Professors, doctors and scientists used to stay weekends and tap over the bushland for fossil fish'" (Pullar & Cook, 2005, p. 11). The geologist F. W. Whitehouse (who later became professor at The University of Queensland) was a dapper young visitor around this time (see Figure 2).

FIGURE 2. The young geologist F. W. Whitehouse with Ms Queenie Jones and friends at 'Oakleigh', the Jones Bee Farm homestead, early 1920s. Photo courtesy of Picture Ipswich, qips-2010-02-16-0074a.

Finding Fossils at the Dinmore Site

The Redbank Plains Formation also outcropped at Dinmore, 7 km to the north-west from Redbank Plains, and both flora and invertebrate fossils were collected from the site until it was covered over in recent years. Stratigraphic or dating comparisons between the locations have not been made. Collecting of fossils from Dinmore is not documented until 1917 for GSQ, and the 1940s for the Queensland Museum. Holdings by the latter are numerous. Riek noted, in regard to the Dinmore site, that "... The Dinmore Beds of mudstones and clay shales have an entirely different lithology so that it is a little doubtful whether they are strictly homologous with the Redbank Plains series" (Riek, 1952a, p. 5). Pole, in his study of the Dinmore flora, interpreted the site as early Eocene (Pole, 2019).

Situated close to the main road and railway line between Brisbane and Ipswich, the clays at Dinmore and its neighbouring suburb Ebbw Vale were the basis of an important Ipswich industry, and were worked since the late 19th century by brick and pottery companies, producing a wide range of pipes, sanitary ware, pottery, bricks and tiles (Ford, 2004). The fossiliferous clays and shales were located primarily south of the railway line, an area with coal mines, quarries and attendant factories, now bisected by the Cunningham Highway.

The Queensland Museum does not appear to have received its first Cenozoic plant fossils from Dinmore until May 1949, collected by J. T. Woods and the Swedish palaeobotanist Oscar Selling, from a "clay pit between Ebbw Vale and Dinmore". The Dinmore site was, over the decades, less well visited than the Redbank Plains site, but it has nonetheless been investigated: Riek described Cenozoic fossil insects (Isoptera and Orthoptera) from Portion 230, and Pole provided an overview of the diversity of the Cenozoic leaf flora from the Dinmore site (Riek, 1952b; Pole, 2019).

Scientific Study of the Redbank Plains Fossils

Extensive scientific analyses of the Redbank Plains fossil material occurred in two main phases: from 1916 until the 1950s, describing some of the fishes (the most prolific fossils on-site) and the insects; and later from the 1980s onwards, after further discoveries and additional research on fish, turtles, insects and other fauna, and also flora.

The eminent entomologist R. J. Tillyard described a fossil lacewing (osmylid) insect from the Redbank Plains Formation (from the Jones Bee Farm) in 1916 – in a paper with Benjamin Dunstan of the GSQ on the Mesozoic and Tertiary insects of Queensland and New South Wales (Tillyard & Dunstan, 1916). The specimen of what was described as *Euporismites balli* was a "wing in yellow rock", which Tillyard recognised as a "very beautiful Osmylid (Neuroptera: Planipennia), allied to *Psychopsis*". "This last is interesting," Tillyard commented to Dunstan on 19 July 1915, "seeing that *Psychopsis illedgei* still occurs (very rarely) on Mount Tamborine [in South East Queensland] . . ." (National Library of Australia (NLA), 1990, obj-2127648725). Tillyard published a second paper in 1923 with a single specimen of a ricaniid (planthopper, Hemiptera) from the same location, which he suggested was "probably Upper Miocene" in age (Tillyard, 1923, p. 19).

The well-preserved fossil fishes from the Jones property had attracted more attention from the GSQ and the Queensland Museum. They were the focus of the first paper dedicated to Redbank Plains fossils, by Edwin Sherbon Hills, then a young geologist at the University of Melbourne and later one of Australia's foremost geological scientists (Hills, 1934). The fish fauna from Redbank Plains included four species: a lungfish (*Epiceratodus denticulatus*), an osteoglossid (*Phareodus queenslandicus*), a gonorynchid (*Notogoneus parvus*) and a percomorph (*Percalates antiquus*).

Hills's initial interest was in the fossil fishes of the Devonian, a subject on which he worked for his doctorate in London. While in London he had asked the GSQ for information on Devonian specimens, but also enquired about Tertiary fish, as he had "already prepared a description of . . . a well-preserved tail of *Epiceratodus* in a pale yellow-brown mudstone" that was in the British Museum (Whitehouse Papers, Box 2).

That specimen of lungfish had been sent to the British Museum for examination in 1927 by the GSQ, identified as "Sagenodus (?) Bundamba, Brisbane. Tertiary spec. for description (Q.G.S. property)", "which we require to be returned" (Natural History Museum, *Dunstan*, 9 September 1927). Hills worked on this fossil while in London, and it was eventually returned to Brisbane, where it is held in the Queensland Museum collection (QMF5956).

The GSQ asked F. W. Whitehouse, then on staff, to gather further Tertiary specimens for Dr Hills, who had returned to Melbourne in early 1932 (GSQ Archives; Hills Papers; Whitehouse Papers). At Whitehouse's suggestion, the GSQ asked Hills in July 1932 if he would prepare a full study of the Redbank Plains Tertiary fishes, using material collected by Whitehouse from Mr Jones's land and a neighbouring property. Hills's 1934 paper was the result. He continued his interest in Queensland Tertiary fishes, publishing a related paper in 1943 (Hills, 1943).

Ostracods were studied by Chapman (1935) and Beasley (1945), which furthered discussion on the likely age of the Redbank Plains beds. O. A. Jones had in 1927 surveyed the Tertiary deposits of South East Queensland, including those at Redbank Plains. Both Chapman and Beasley concluded that the environment was lacustrine and freshwater with, according to Chapman, occasional marine incursions, although this interpretation is not widely accepted.

The entomologist Edgar Riek completed a study of the fossil insects in 1952 (Riek, 1952a). He described the lithology and stratigraphy of the Series and surveyed the fauna of the deposit as it was then known, and its significance. Riek also described two new fossil insects (both Mecoptera or scorpion flies) and included a re-description of the neuropteran (lacewing) named by Tillyard in 1916, with new material collected by University of Queensland personnel.

Riek produced three further papers on Redbank Plains and Dinmore insects (Riek 1952b, 1954, 1967), describing several Diptera (flies), an isopteran (termite) and orthopteran (grasshopper) from Dinmore, and an update on his original mecopteran. Lambkin followed up much later with a record of a megalopteran (alderfly), and additional work on the neuropteran and mecopterans (Lambkin, 1987, 1992, 2018), while Houston (1994) studied additional termites and planthoppers. Willmann (1977) erected a new family to accommodate Riek's *Austropanorpa* (1952). The insect taxa described from Redbank Plains comprise representatives of seven extant orders and ten extant families, the most diverse Cenozoic insect fauna in Australia.

As more lungfish fossils were found at Redbank Plains, including toothplates, skull anatomy, scales and body structures, Kemp in 1997 referred the Redbank Plains "*Epiceratodus*" to *Mioceratodus gregoryi*, a new genus of Cenozoic fossil lungfish widespread across central and northern Australia, as she considered it indistinguishable from this widespread taxon (Kemp, 1977, 2018).

Reptiles also received attention, following Riek's highlighting of reptilian remains in his 1952 paper. Lapparent de Broin and Molnar in 2001 identified five freshwater turtle taxa from Redbank Plains, representing both main Australian chelid groups, the *Emydura* and *Chelodina*, including a new species of the latter. They were noted to be "not only the oldest described Australian Cenozoic turtle material, but also the oldest Australian specimens definitely attributable to freshwater chelids" (Lapparent de Broin & Molnar, 2001, p. 45).

In addition, a bird foot had been discovered, similar to dromornithids (large flightless birds) and potentially an early member of the clade – indeed the oldest such member from Australia (Vickers-Rich & Molnar, 1996). As yet, no amphibian or mammal remains have been identified from the Redbank Plains Formation.

Flora from Redbank Plains and Dinmore have been extensively collected, with research done on the Dinmore fossils. Selling (1950) undertook some study of Australian Tertiary plants, including a specimen from Dinmore, and Churchill (1969) established *Lygodium dinmorphyllum* in 1969. Since that time it has been Rozefelds and others who have written on both Redbank Plains and Dinmore plants, specifically *Eucalyptus* fruits, a survey of Australian *Lygodium* (including Dinmore material) and a new genus of water fern (Rozefelds et al., 1992, 2016; Rozefelds, 1996). Pole's 2019 study of the Dinmore flora shows that angiosperms dominated, with 20 taxa identified.

The Queensland Museum concluded that:

> . . . The array of leaf types suggests that the local environment may have been rainforest. Some of the leaves are comparable to modern rainforest plants belonging to the laurels (Lauraceae), banksias and macadamias (Proteaceae) and eucalypts and myrtle (Myrtaceae) families (Queensland Museum, 2015, p. 219).

See Figure 3 for examples of Redbank Plains Formation fossils.

The Fossil Site Under Threat

That the Redbank Plains fossil site still exists in 2022 was unlikely to have been predicted in the 1970s. As was discussed above, the Redbank Plains area has been known since the late 19th century to have coal reserves. The named mining areas "Redbank Plains" and "Redbank Plains Extension" (Cranfield & Green, 1983) formed the easternmost part of the Ipswich coalfield and took in large areas of what today are the suburbs of Redbank Plains, Bellbird Park and Augustine Heights. Further core drilling in these areas took place between 1967 and 1970, and results indicated that "some of the Blackstone [Formation] coals persist in workable conditions . . . at depths of 500 to 600 feet" (Queensland Department of Mines, 1969, p. 95).

The potential for mining of the coal in Redbank Plains was therefore real. Mengel & Carr, in GSQ's survey of the Ipswich coalfield, outlined activity in the Redbank Plains Extension as follows:

> Most of this area is a Departmental Reserve, but Rylance Collieries and Brickworks Pty Ltd hold coal mining leases and an authority to prospect over the eastern part near Woogaroo Creek . . . The coal seams do not crop out and they deteriorate to the east . . . This part of the area has been included in the southern part of a satellite town planned by the Queensland Housing Commission, and the remainder of the area is being sub-divided in a similar manner to Redbank Plains (Mengel & Carr, 1976, p. 14).

GSQ recognised that "the area, because of its geographic location and pleasant environment, is ideally suited for semi-rural residential subdivision . . . The activities associated with a deep shaft mine may not be acceptable".

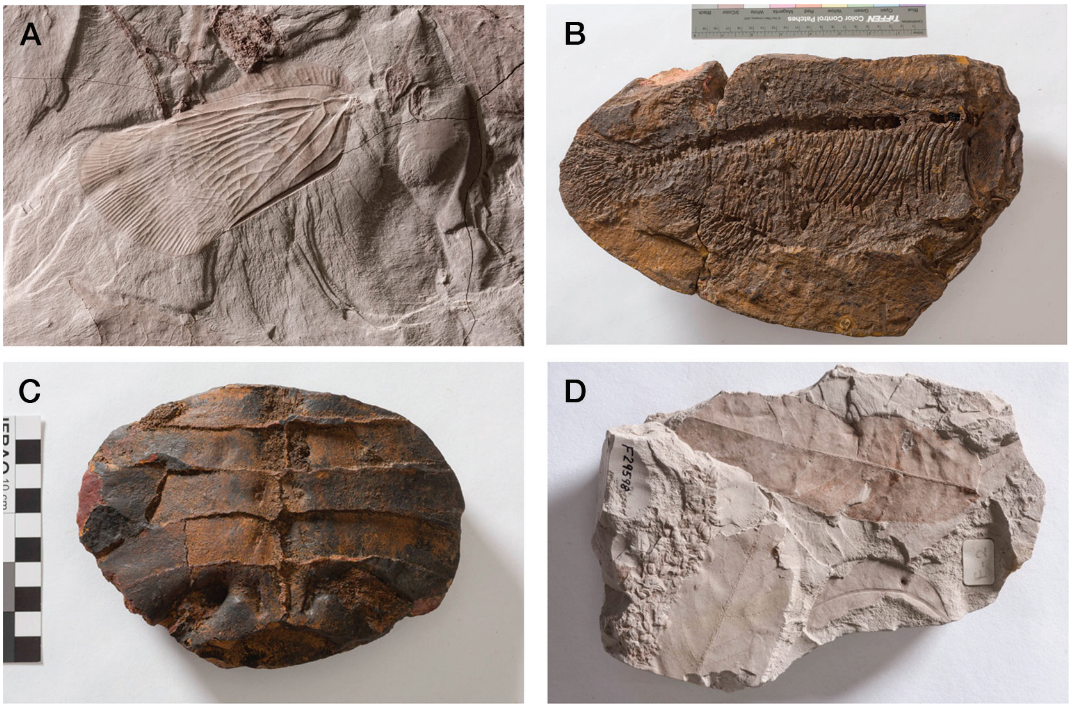

FIGURE 3. (A) QMF14808, wing of a planthopper *Scolypopites* sp.; (B) GSQF1960, body of osteoglossid fish *Phareodus queenslandicus*; (C) QMF37913, internal mould of carapace of an emyduran turtle; (D) QMF29598, leaf and seed material from Dinmore. Permission to use all images provided by Queensland Museum (QM). Photographer: Peter Waddington, QM.

Potential mining had become more difficult when the Queensland Housing Commission purchased land in July 1971 for a new housing estate, which fully incorporated the fossil site and beyond. The area of over 600 acres of land was intended to provide a suburb for some 10,000 residents in due course, a substantial boost to the local population (Anon., 1972).

As well as these plans for residential expansion, there was also a proposal by the State Electricity Commission for the siting of a thermal power station where the Augustine Heights and Brookwater suburbs are now located, only 2 km from the just-announced new housing development. GSQ was requested in March 1973 to undertake a geological assessment of the proposal: only one borehole was drilled, but it revealed that the Tertiary sediments below were unsuitable for high-bearing loads (Barker, 1973).

An environmental impact study was conducted, which showed that the proposed power station site would incorporate several hundred acres, coal would be accessed from a mine already projected within Mining Lease 587 north of Jones Road, a water pipeline would require a 66-foot easement to cut directly across the fossil site land, and visual, noise and air-pollution impacts would be significant on the surrounding areas (Coffey & Hollingsworth, 1973). The project did not proceed.

Despite GSQ's negative views about exploitation of the coal reserves, exploration continued. From the late 1960s, Rylance Collieries and Brickworks was actively drilling and planning for coal mining in the area. In 1979 the Housing Commission abandoned its proposal for a new subdivision and sold the land in its entirety to Rylance for $620,000, of which $558,000 was controversially loaned to the company for this purpose, including a three-year non-repayment period (Queensland Parliament, 1981).

The company quickly gained approval for new mining leases at Redbank Plains, formed a joint venture company with Japanese interests and undertook further drilling. This showed that open cut mining would be difficult, but that 59 million tonnes of coal were present from 100 to 400 metres below the surface, with approximately 10 million tonnes of mineable clean coal. The coal was "good steam coal with a low sulphur content and high ash fusion temperature", and most of this was for export to Japan (Redbank Plains Resources, 1982, p. 6).

The Federal Government approved the proposed Japanese investment (Foreign Investment Review Board, 1982), and the Queensland Government considered the construction of a railway line to transport coal from the mine. Nonetheless, after such extensive exploration work, political manoeuvring, government approvals and commercial arrangements, the mine did not go ahead. This was because of organised opposition from local government and local residents (Murray, 2010), plus the significant costs associated with the infrastructure, transport, freight and remediation of a mine and its dedicated railway, in an already settled and rapidly developing suburban area (Queensland Treasury, 1979–1983).

At no stage, however, in any of the public objections, court proceedings, environmental impact reports or government statements at the time, was any reference made to the Redbank Plains fossil site, either as a part of the local natural environment likely to be impacted by the mine development, or as a scientific issue to be considered.

In short, the recognition by the GSQ of the palaeontological and scientific significance of the site, the local knowledge of the fossils through the long ownership by the Jones family and the research conducted over 80 years had not affected the decision making by government or impacted on the wider public. The geological heritage and scientific value embodied in the fossil site were simply part of an exploitable landscape and had no place in development planning at the time. The discontinuation of the proposed mine in 1983 was purely a result of the commercial and infrastructure costs involved, and political and press agitation about the impact on local lifestyle and amenity – neither science nor heritage had any place.

Status of the Redbank Plains Formation Sites After 1990

The original Jones house block was held by the Jones family until 1969 and is now partly zoned 'Conservation'. Parcel conditions include 'Character Place – Historical Miscellaneous Places' (Ipswich City Council PD Online; Buchanan Architects, 1997). The house itself, the original Bee Farm residence 'Oakleigh', is not listed on the Queensland Heritage Register but is recognised by the Ipswich City Council as a heritage site.

The neighbouring block, originally owned by Jones but later acquired by Rylance, was re-surveyed in 1992 to fully incorporate the known outcropping fossil area and was acquired by the Ipswich City Council as a conservation reserve. Subsequently, housing and a primary school were built on surrounding land. The fossil zone remains intact as of June 2022, is zoned 'Conservation' and also contains as a parcel condition 'Character Place – Historical Miscellaneous Places'. It is owned and managed by the Ipswich City Council, which is aware of its scientific importance.

The 'Redbank Plains Fossil Site' is listed on the Commonwealth Register of the National Estate as Indicative Place 18128. The site has been recognised in publications by the Australian Heritage Council (2012) and by the Queensland Museum (2015).

The Cenozoic fossil site at Dinmore is now inaccessible. It is part of an area which remains available for clay mining and associated industrial operations, and is subject to future development.

Conclusion: Preserving Scientific and Geological Heritage

Australia's abundant palaeontological resources are generally poorly protected and preserved. Apart from a limited number of World Heritage or similarly important localities (such as Riversleigh in Queensland), the vast majority of fossil deposits across the continent are unprotected and do not fit easily into existing legislative or administrative conservation regimes (Creswell, 2019). Geo-conservation has not been part of the vocabulary of environmental protection in Australia, and the field evidence of the fossil history of Australia, a part of our national geological heritage still largely under-explored and under-studied, remains at risk.

Fossil sites are today sometimes recognised by local communities, particularly if they have been studied over many years (e.g. the Chinchilla Local

Fauna in southern Queensland (Wilkinson et al., 2021)). Sometimes they are managed to advance the economic and tourism interests of the community: for example, Ulladulla in New South Wales, or the Winton and Eromanga dinosaur sites in outback Queensland, all now popular palaeo-tourism destinations.

In Australia, heritage sites of national importance are registered under the National Heritage List and protected under the *Environment Protection and Biodiversity Conservation Act 1999*. Five fossil sites are included therein: Naracoorte (SA), Riversleigh (Qld), Lark Quarry (Qld), Nilpena Wilpena (SA) and Yea (Victoria). A search of the National Heritage Database yielded 118 sites where the term 'fossil' was relevant to their significance, but most of these are only registered and are not formally recognised under the Act.

Although two Queensland fossil sites are on the important National List, no fossil localities are included in the Queensland State Heritage Register. This Register refers to only one "geological formation" (the Glasshouse Mountains near Brisbane), as most entries refer to the history of human activity. The *Queensland Nature Conservation Act 1992* (as amended, Section 8) does recognise not just ecosystems but "all natural and physical resources, and natural dynamic processes" as coming under protection through national parks and related conservation areas. Some areas with fossils come within national parks or "Nature Conservation (Protected Areas)", but the Redbank Plains site is not of itself recognised under the Act or associated regulations.

More often, fossil sites are ignored. In the case of the Redbank Plains Formation, it has taken over a century for the science to be documented (with new discoveries continuing), but the sites have been threatened for 50 years, and protection of their scientific values is not assured.

The housing, population and industrial development pressures on maintaining the scientific integrity of the Redbank Plains Formation type locality are real. The enduring scientific value of this fossil site will depend on its status as a conservation reserve being maintained and managed into the future. The strong heritage focus of the Ipswich City Council potentially provides a basis for recognition of geoheritage, as the Council already manages several conservation parks, including Denmark Hill, internationally renowned as a Triassic fossil site for over a century (Rix, 2021). In the meantime, the Redbank Plains fossil site continues to be investigated and its significance promoted.

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The palaeontological collections of the Queensland Museum, The University of Queensland and the Geological Survey of Queensland are all housed within and managed by the Queensland Museum, Brisbane. All contain fossil material from the Redbank Plains Formation. These, in addition to archival records of the three organisations held within the Museum, yielded data on collecting history, locations and personnel. The online geological and historical resources of the Queensland Department of Natural Resources and Mines through the GSQ Open Data Portal were also extremely valuable, as were archives held at The University of Queensland, the National Library of Australia and the Natural History Museum (London). At the Queensland Museum, assistance on this project from Dr Andrew Rozefelds, Kristen Spring and Joanne Wilkinson is gratefully acknowledged, as is preparation of the figures by Dr Michael Rix. Comments from two reviewers were much appreciated. Sincere thanks are also due to Lyn and Neil McLean, for their committed support over many years for Redbank Plains fossil research and the heritage of the site.

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Early-career Researcher Abstracts

Using DNA Information to Breed for Disease-resistant Strawberries

Katie O'Connor[1], Jodi Neal[1], Apollo Gomez[1] and Joanne De Faveri[2]

Abstract

Strawberries are susceptible to many diseases that cause damage to leaves and fruit, such as powdery mildew. Many chemical sprays are used to control disease, but there is an industry, environmental and societal push to move away from fungicides. Breeding for disease-resistant varieties offers an alternative approach, and DNA information can be used in this strategy. We identified multiple genetic markers linked with resistance to powdery mildew in leaves and fruit using a statistical modelling method called 'genome-wide association studies'. We also used DNA information across the entire genome to predict the susceptibility of different strawberry varieties. These results will help Queensland strawberry breeders to identify candidate varieties that are resistant to powdery mildew without expensive and time-consuming disease screening trials. These statistical methods can also be applied to other diseases, as well as yield and fruit quality traits.

Keywords: strawberry, powdery mildew, fungus, genomics, DNA

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Optimising Facility Location and Sizing for Coral Aquaculture Production

Ryu B. Lippmann[1,2], Kate J. Helmstedt[1,2], Mark T. Gibbs[3] and Paul Corry[1,2]

Abstract

Active restoration is increasingly being seen as a viable method for reversing global coral reef decline in many locations. We assess coral aquaculture production as a restoration strategy to grow and deploy cultivated corals to specified reef locations in the wild. We formulate and solve a novel mathematical programming model of the facility location and sizing problem for coral aquaculture. This is used to address crucial strategic decisions regarding the number, location and sizing of facilities, as well as operational decisions on growth time to minimise total costs. The characteristic function for coral survival based on facility growth time is shown to be critical in determining the optimal growth time. Computational experiments demonstrate that the optimal number and location of facilities are sensitive to changes in the reefs serviced and the relative weighting of capital and operational cost parameters. This demonstrates the value of data clarity to minimise total costs.

Keywords: optimisation, facility location, facility sizing, coral aquaculture, reef restoration

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Boomerangs Shape Stone Tools in Ancient Queensland: Experimental Archaeology and Traditional Knowledge Reveal a New Function of the Most Iconic Indigenous Tool

Eva F. Martellotta[1] and Paul Craft[2,3]

Abstract

Without a doubt, boomerangs are one of the Sunshine State's symbols. But forget everything you know about their 'returning effect'. Whereas returning boomerangs were only used for games and learning purposes, non-returning boomerangs were complex, multifunctional tools. They played a crucial role in Indigenous communities' daily lives in Queensland and other parts of Australia. In our work, we put together Traditional knowledge and experimental archaeology to investigate a forgotten use of boomerangs: modifying the edges of stone tools. This activity is fundamental to producing a variety of stone implements, each of them with a specific function. In our study, experimental replicas of boomerangs proved very functional to shape stone tools. Our results are the first scientific proof of the multipurpose nature of these iconic objects.

Keywords: Australian archaeology, wooden tools, hardwood boomerangs, multipurpose

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Testing Strontium for Estimating Weaning Ages: Implications for Marsupial Life History Reconstruction

Maya Bharatiya[1,2], Tanya M. Smith[1,2] and Christine M. Austin[3]

Abstract

Documenting the transition from infant nursing to an adult diet can shed light on the reproductive strategies of mammals, including the enigmatic *Diprotodon* and other megafauna that once roamed Queensland. Concentrations of the trace element strontium in primate teeth have been used as a proxy to estimate this transition. An influential model posits that strontium levels (relative to calcium) should be low during initial nursing due to limited strontium in milk, increase with the introduction of solid foods that contain higher amounts of strontium, peak at the cessation of suckling, and slowly decline as the gut begins discriminating against strontium in favour of calcium. This study tests this model by assessing trace elements in 13 human and non-human primate first molars (M1) with laser-ablation, inductively coupled plasma mass spectrometry. Only 54% of M1s had a peak in strontium immediately after the cessation of suckling, and none of these showed a subsequent decline in strontium. Alternative approaches are needed for inferring the weaning ages and life histories of ancient marsupials.

Keywords: strontium, life history, tooth development, dental anthropology, marsupials

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What Can Ancient DNA Bring to the Identification of Fallen Australian War Casualties? Pioneering Methodologies at Queensland-based Ancient DNA Facilities

Sally Wasef[1,2], Ido Bar[3], Natasha Mitchell[4] and Kirsty Wright[4]

Abstract

A fundamental problem in the identification of recovered Australian remains is that the current approach relies on forensic DNA methods developed for modern criminal casework, which are not suitable for degraded DNA. At the Griffith University's Australian Research Centre for Human Evolution Ancient DNA Facility, we have been conducting pilot research involving DNA from the remains of a WWI Australian soldier recovered from Belgium. We have shown that advancements in extraction, next-generation sequencing and bioinformatics of ancient DNA provide a more informative approach for identifying fallen soldiers than traditional forensic methods alone. We successfully retrieved whole-genome data, revealed the maternal (mtDNA) and parental (Ych) haplotypes, and some phenotypic characteristics that can be used to target identification efforts. This pilot study highlights methodological advancements and the importance of genealogical searches of living relatives and their DNA to identify recovered remains and bring closure to their loved ones. Our methods have implications for future ancient DNA recovery efforts in facilities at the Queensland University of Technology and across Queensland.

Keywords: ancient DNA, WWI remains, paleogenetics, next-generation sequencing, target enrichment

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Tidal Restriction Leads to Enhanced Methane Emissions in Tropical Australia

Charles Cadier[1], Nathan Waltham[2], Adam Canning[2], Scott Fry[3] and Maria F. Adame[1]

Abstract

In Queensland, tidal restriction of coastal wetlands alters their hydrological connection and creates freshwater-impounded wetlands, increasing methane emissions. We investigated greenhouse gas emissions from tidally restricted wetlands and compared them with adjacent tidally connected wetlands (saltmarsh and mangroves). Furthermore, we investigated the influence of seasons and soil physicochemical parameters on greenhouse gas emissions. Tidal restriction leads to significantly higher methane emissions compared to natural coastal wetlands. Soil redox, carbon density, nitrogen density and moisture were all significantly correlated to methane emissions. Seasons influenced greenhouse gas emissions, with higher emissions in summer. Overall, tidally restricted wetlands were emitting 2175 mg $CO_{2-eq}.m^2.d^{-1}$, two orders of magnitude higher than tidally connected wetlands which emitted 18 mg $CO_{2-eq}.m^2.d^{-1}$. This research is supporting tidal restoration in Queensland as a cost-effective strategy to mitigate climate change as it has the potential to enhance blue carbon burial rates and avoids long-term emissions of methane.

Keywords: tidal restriction, coastal wetlands, methane, tidal restoration, soil indicators

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Are Tropical Mountaintop Trees Constrained in Their Distributions by Physiological Limitations? Thermal Adaptation and Acclimation to Climate Change

Arun Singh Ramesh[1,3], Alexander W. Cheesman[1], Darren M. Crayn[1,2] and Lucas A. Cernusak[1,3]

Abstract

Habitat suitability for most tree species restricted to the wet tropical mountaintops of Australia is predicted to decline with climate change. This is especially concerning because no available alternative habitat exists for species to migrate, and their growth responses to warming are understudied. We present a study investigating the effects of warming on an ecologically important taxon, *Flindersia* spp., distributed across an elevation gradient in the Australian Wet Tropics. We test: (a) whether tropical mountaintop tree species are constrained in their distributions by physiological limitations to their thermal environment; and (b) whether species display an ability to adapt and/or acclimate to future warming. We first explored trends in species' *in situ* adaptation by studying leaf traits among congeners paired with environmental variables, and then evaluated plant physiological and growth responses under experimental soil nutrients and growth temperatures. We found that field trends in fundamental leaf traits with elevation were strongly driven by climate – decreasing temperatures, increasing soil moisture content and decreasing soil nutrient availability – and under experimental growth conditions showed increasing growth under warmer conditions, but then either declined or did not significantly change for upland and mountaintop species under resource-rich conditions. These modifications were associated with limitations in their photosynthetic biochemistry and selection of pathways favouring either growth or defence under resource-poor conditions. Our research findings have implications for conservation of these species in these fragile ecosystems under future warming.

Keywords: habitat suitability, wet tropics, *Flindersia*, leaf traits, fragile ecosystems

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Royal Society of Queensland
Reports

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The Imbalance of Power between Urban and Rural Populations When Addressing Sustainability While Burdened by Indifferent Politics

Ross A. Hynes

Overview of the Status Quo

It takes only a brief scroll through a mainstream newspaper to form the conclusion that Queensland and Australia's progress towards sustainability in general, and environmental protection in particular, is lacklustre, to put it mildly. The passage in mid-2022 of national legislation setting a carbon target is welcome. Nevertheless, every day there seems to be some new announcement of a climate tipping point exceeded, another approval of a fossil fuel project, in some areas a debatable logging operation and elsewhere another story about the inability of the Murray-Darling Basin Plan to rein in overallocation.

Even so, are our expectations and current official strategies unrealistic? Are there just *not enough* skilled people at the right place and time to devise and implement effective environmental policies? Will this always be the case under the present economic paradigm? Is it necessary for our society to significantly re-order the way public budgets are generated and allocated? How do governments and businesses work more cooperatively and intelligently together? If agreement can be reached that collaboration is necessary, how then can we effectively draft strategies to be fit-for-purpose for highly astute interventions in what is clearly a very short window of opportunity to reverse the adverse trends? A window that is likely to be diminishing with the accelerating impacts of climate change! Where is the urgency in our parliaments and business community for this to happen?

We desperately need to upgrade our national communications infrastructure to significantly enhance our response capabilities. Recent 'unprecedented' extreme events in the form of droughts, fires and floods have accelerated the urgency of improving rapid, high-quality messaging and knowledge transfer across the continent. They have also exposed a woeful lack of insightful planning, essential infrastructure development and necessary emergency services. '*She'll be right mate!*' is just not good enough nowadays, if it ever has been. We also need to establish an economic framework that with some realism addresses these problems. The current economic paradigm does not.

The limitations of contemporary political systems in their ability to achieve a sustainable biosphere and low-emission life-support system for *Homo sapiens*, whilst pre-empting and managing natural disasters of differing magnitude, frequency and intensity as climate change intensifies, have recently become frighteningly obvious. Both democratic and autocratic governance structures are presently largely failing. Major urgent legislative reform is needed. Quinn (2020), in a submission to the independent review of the *Environment Protection and Biodiversity Conservation Act 1999*, outlined amendments that seek to address the deficiencies of its statutory regime. However, parallel complementary legislation would be needed to provide a comprehensive legal framework as the entire physical, social and information infrastructure of our society needs to be re-engineered. Even with a reformed legislative base, genuine political will and broad community commitment, it is not certain that there is still time to redress much of the current predicament in Queensland and Australia-wide before

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cascading biophysical challenges overwhelm our institutional capacities.

Assuming consensus can be achieved to allow scientific knowledge – generated in the laboratory and in field study sites, in tandem with rigorous data management, data analysis and perceptive modelling – to be scaled up and applied at state and national levels and in turn globally, can we actually do it? Or will the 'ghosts in the human machine' (past human societal dysfunctional behaviours) lead ultimately to our demise as a civilisation? It has occurred numerous times throughout human history. Upscaling – that is, applying insights about local ecological systems and individual actions to a broader canvas to solve problems of great magnitude – is crucial to any solutions. The catchphrase '*Think globally, act locally*' has been around for more than 40 years, but we need to do more than this. Clearly, upscaling is an essential process in seeking solutions to most of the sustainability challenges we face, but the gloomy news arriving daily in our newspapers and inboxes suggests that existing institutional infrastructures will not allow this to happen.

Downscaling will also be needed, such as trimming and simplifying supply chains in size and scope to reduce the dependency of communities upon resources transported over long distances. This process is needed to reduce over-exploitation or wastefulness of resources and energy, which are the inevitable consequence of relying upon economic profit and market forces to structure our society's transactions in goods and services. A serious and urgent aim should be for most regional systems to become as sustainably self-sufficient as possible. The next 100 years will undoubtedly present the greatest challenge to survival that *Homo sapiens* / '*Homo economicus*' has yet had to face.

Building Resilience into Social-ecological Systems

How Does Resilience Relate to Sustainability?

A basic definition of resilience is 'the capacity of a system, be it an individual, a forest, a city or an economy, to deal with change and continue to persist with relevance'. Lack of resilience forces the system to focus on short-term needs and take any action possible to survive – this behaviour ultimately limits the ability to achieve long-term sustainability.

A basic definition of sustainability is "the ability to meet the needs of the present without compromising the ability of future generations to meet their own needs" (adapted from a quotation by Gro Harlem Brundtland, Norwegian Prime Minister, 1987). Presently we are neither satisfying this definition nor adequately seeking and facilitating system resilience.

System Resilience

Natural scientists have led the way in exploring ecosystem resilience. Now resilience in social-ecological systems (SES) well deserves to be a major theme of research. A significant beginning has been theoretically achieved in this complex area over the past two decades (Biggs et al., 2021). However, progress in putting this into practice has been slow. The subject is comprehensively and accessibly overviewed in Brian Walker's book *Finding Resilience: Change and Uncertainty in Nature and Society* (2019). Discussing his book, Walker (2020a) states that resilience is about change in response to a disturbance: "changing the ways various parts of the 'system' are connected, emphasising some and de-emphasising others. It's the capacity to absorb disturbance and re-organise so as to keep functioning in much the same kind of way – to have the same identity. In systems terms this means staying away from threshold-levels".

In a subsequent paper, Walker (2020b, p. 1) further explained that: "There are two key parts to resilience: first, learning how to identify and stay away from (or where necessary cross) such known tipping points/thresholds and second, to avoid crossing as yet unknown and unsuspected thresholds, as we learn about the attributes of a system that confer resilience […]. Possibly the most common misinterpretation of resilience is 'bouncing back'…" to the original system state. This is not resilience in any contemporary ecological sense. Ecosystems are continuously changing, albeit often at different component scales to maintain resilience. Walker (2020b, p. 1) continues: "There is [also] confusion in regard to the terms 'robustness' and 'resilience'. 'Robustness' is generally taken to mean the ability to resist a disturbance by not changing; sometimes referred to as 'engineering resilience'" (Holling, 1996, cited in Walker, 2020b). Further, "The two contrasting aspects of stability – essentially one that focuses on maintaining efficiency of function (engineering resilience) and one that focuses on maintaining existence of function (ecological resilience) – are so fundamental that they can become alternative paradigms, whose devotees reflect traditions of a discipline or of an attitude more than of a reality of nature" (Holling, 1996, p. 33).

Walker further identifies (2020b) a firming list of attributes that promote general resilience and describes these: viz. *response diversity (diversity of species and their potential for various advantageous resilient responses)*, *exposure to disturbance*, *being modular (system modules not being under- or over-connected to sustain resilient advantages)*,"*being able to respond quickly to shocks and changes in the system*, *being ready to transform if necessary*; *thinking, planning and managing across scales* [and] *guiding not steering*" (p. 2).

In conclusion, Walker (2020b, p. 2) offers a number of key points:

1. "Resilience is largely about learning *how* to change in order not to *be* changed."
2. "It is necessary to consider both the resilience of particular parts of a system to specific threats, as well as resilience in general, of all parts of the system to all kinds of disturbance."
3. "Trying to protect a system by keeping it in a constant state reduces its resilience. Exposure to the full range of [environmental] and [relevant social] variation is necessary for maintaining and building resilience."
4. "Deliberate transformation of a system is sometimes necessary for it to continue delivering what is fundamentally of value to society."

I intend to explore the challenge of building resilience into social-ecological systems in relation to cross-scale issues in a paper in progress that should be published in 2023, tentatively titled: *Challenges of managing scale for sustainability – from science to application*.

Hurdles in the Path to Effective Resilience Policy

Let me now change tack and return to the earlier discussion of the problems caused by the power imbalance between urban and rural populations. This becomes particularly challenging when addressing sustainability in the absence of adequate infrastructure and this while being burdened by indifferent politics. These problems are seriously exacerbated when trying to operate within an 'out-of-date' economic paradigm. Here I seek to bring the narrative back to the Society's experience of the past 12 months. The rangelands of Australia cover about 80% of the continent (Sattler, 2020) with a similar but slightly lower percentage in Queensland. Here they support <1 person per km^2 of the state's population with ~0.1 person per km^2 in the area defined as the Outback[a] (Queensland Government, 2017, 2022).

On behalf of the Rangelands Discussion Group, since 2019 the Society has sought financial or institutional support for the kind of whole-systems analysis and dialogue that is necessary to address the ills identified in the first half of this paper. But we have failed. For all of the valuable scientific and economic knowledge generated and synthesised in the Rangelands Dialogue and its associated outputs, there has been a lack of interest in deep engagement by most sectoral groups. Does wide-window thinking and a whole-systems perspective pose too much of a threat to entrenched ways of rural and remote land management? How can we cut through? A paper by Lloyd and George (2022) in these *Proceedings* provides a rigorously developed example of a 'cut-through path' that addresses the challenges to promote and gain consensus of perception among pastoralists regarding climate change and, potentially, a changed approach to rangelands management, use and sustainment. Their excellent grounded strategy deserves wide cooperative support.

In another case, the Royal Societies of Australia have not been able to attract any significant

[a] Overall, Queensland has 2.5 people per km^2 (Population Australia, 2022), with 68.6% living in SEQ. Even so, it is comparatively decentralised when compared to other states, with numerous coastal cities and towns to the north and two inland cities. Nevertheless, vast open areas make up the majority of the state's land tenure in which the rangelands are located. The Queensland Outback is 834,679.8 km^2 in area, which in 2016 had a population density of 0.015 per km^2 with 79,700 persons including 26,560 Indigenous persons. Whereas the Indigenous population is increasing, there have been recent drops in other sectors of the population.

logistical support for their nation-wide, insightfully developed and delivered 'Stewardship of Country' series of webinars to proceed to the next stage, viz. a policy hub. Why?

The range of insights represented in our *Proceedings* and forums related to broader sustainable land management strategies during this time have exposed an absence of government institutional infrastructure to carry them into public policy. This is one of the major barriers to achieving progress in these areas. A compelling example of this, concerning the impacts of coal seam gas mining on farming, is critically examined in these *Proceedings* by Dart et al. (2022). Other barriers, particularly in the rangelands, include low population density and lack of skilled people who are long-term inhabitants, across the full spectrum of key trades, professions and other occupations.

I give credit to many of our authors, including Peter Dart and co-authors, who are crossing disciplines in their research work. Another excellent example is the widely acclaimed *Springs of the Great Artesian Basin,* Special Issue of the *Proceedings*, Volume 126 (2020).

I extend praise and encouragement to the early-career researchers and say how galling it has been recently to have had to decline more than 15 excellent applications for grants from our Research Fund because of a lack of ongoing funding support.

Why have we been corralled in this way? It is perhaps simple: behavioural change requires effort and sometimes pain. Governing bodies are political and tend to act to maintain continuity of power, often at the cost of achieving rational outcomes which would benefit the majority of stakeholders. At the other end of the community spectrum, many rural and remotely located people are already steeped in extreme physical and mental stress, and some are experiencing high levels of psychological trauma (Shrapnel et al., 2000; Hossain et al., 2012).

Another solemn factor, which reflects this situation, is the significant difference trending in suicide rates per 100,000 people between large cities (~10), outer regions (~18), remote regions (~17) and very remote regions (~ 25) (Australian Institute of Health and Welfare, 2022). For communities in these latter circumstances there is often inertia, high economic risk-aversion and resistance to change. But change may be welcomed by some, and even more if they understand potential positive outcomes. To the contrary, however, we mainly appear to be slaves to the crudeness of the push–pull of supply-and-demand market forces, whilst continuing to operate largely disconnected from ecological services and associated unpriced values such as those intrinsic to our culture.

Rethinking Pathways to Global Resilience in an Alternative Economic Framework

Are there novel pathways to a more intelligent economic future that also imbue options for resilience in social-ecological systems? Let us briefly explore one of these: *a safe space for the future of humanity operating in a genuinely ecologically viable but workable economic framework*.

Initially, Rockstrom et al. (2009) of the Stockholm Resilience Centre, Stockholm University, with 28 associate scientists, identified nine planetary boundary entities that regulate the stability and resilience of the Earth System. These are: climate change; ocean acidification; stratospheric ozone; biogeochemical nitrogen and phosphorus cycles; global freshwater use; land system change; and the rate at which biological diversity is lost. The two additional, undetermined planetary boundaries are chemical pollution and atmospheric aerosol loading. Rockstrom et al. (2009) estimated that humanity has already transgressed three planetary boundaries: viz. for climate change, rate of biodiversity loss, and changes to the global nitrogen cycles. And even though the framework was thoroughly revised by Steffen et al. (2015), the complexity and number of novel artefacts (new substances, modified life forms, new types of engineered materials and organisms), which could form an additional category, has probably expanded significantly since then. Transgressions may overshoot certain safe boundary thresholds of the defined ecological ceiling, e.g. excessive, cumulative nitrogen and phosphorus loading. Their proposed ecological ceiling boundaries are first estimates only. Filling knowledge gaps will require major advancements in Earth System and resilience science. The proposed concept of planetary boundaries lays the groundwork for shifting our approach to governance and management, away from the essentially sectoral analyses of limits to growth aimed at minimising negative externalities that are still tied to the prevailing economic paradigm. This will enable us to move towards a more enlightened understanding and delineation of the safe space for human development.

Raworth (2012) followed this work by developing the Doughnut Economic Model of planetary boundaries. This explains the concept of the safe space for humanity in the biosphere. She incorporates an inner boundary named the 'social foundation'. This delineates a range of global basic human needs and estimates of the proportion of undershoots, e.g. inadequate food, water, housing, etc. Her later publication (Raworth, 2017a) presents an accessible, logical case for a paradigm shift in economics for the 21st century and provides seven ways to consider the need and potential of its application. These include moving from a GDP-dominated goal to a doughnut-shaped economic goal, which has the following attributes: an embedded economy[c]; social, adaptable humans; the recognition of the dynamic complexity of systems; distributive income by design; income equity achieved by regenerative design[d]; and becoming an economy agnostic about growth. Figure 1 introduces and provides a brief explanation of the concepts involved.

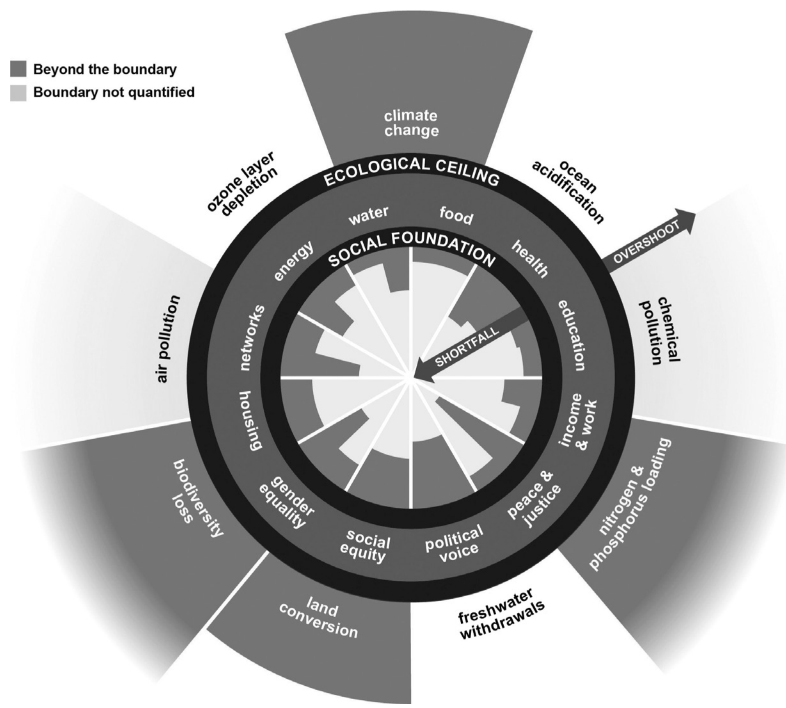

FIGURE 1. Shortfalls and overshoots both sides of the doughnut's boundaries. The black circles show the ecological ceiling and social foundation, encompassing a safe and just space for humanity. The grey wedges below the social foundation schematically show the proportion of people worldwide falling short on life's basics. The grey wedges radiating beyond the ecological ceiling show the overshoot of planetary boundaries. The light-grey wedges and white areas indicate that the overshoot is not yet adequately quantified. The twelve dimensions covering human welfare are shown in white in the inner circle of the doughnut. These describe the minimum standards adopted for human wellbeing by all UN nations in 2015 as Sustainable Development Goals (Raworth 2017b). A complete explanation of the data used is provided in an Appendix to Raworth's (2017a) book on pages 295–299. (Modified figure is reproduced under a CC BY 4.0 licence from Raworth 2017b, p. e48. Figure modifications include changes to colour, and basic changes to shape, thickness, font type and size.)

[b] One where economic values are not necessarily the preeminent values, and the public interest is determined by social and political processes.

[c] A process-orientated, whole-systems approach to design.

The 'doughnut' she suggests might act as a 21st-century compass to guide us forward (Raworth, 2017b). Attenborough & Hughes (2020) strongly affirm this innovative framework, which can intelligently help create an effective map to enable humanity to navigate our path to a more sustainable future.

Concluding Remarks

My recognition of the need for a new economic paradigm began in the early 1970s with the publication of *The Limits to Growth* (Meadows et al., 1972). It was reinforced when I attended the launching of *Our Common Future* (World Commission on the Environment and Development, 1987) at the 4th World Wilderness Congress in Denver, Colorado, USA. It was clarified in reading Pearce et al. (1989) and Young (1992), who exposed the disarticulation of the current economic paradigm from ecological services. They also identified the lack of responsible incorporation of option, bequest and intrinsic (aesthetic, biological and cultural) values in resource-use decision-making and implementation. These are transgressions for which humanity has never truly paid any real price.

Another factor seldom questioned globally at that time[d] was overpopulation of previously viable habitable areas, which with climate change are beginning and will continue to produce millions of 'climate refugees' over the next decades. Ironically, in Australia and particularly the rangelands in Queensland and the tropical north generally, we lack a rational ethical economic platform to rigorously address overall sustainability and resilience. Perhaps some of the climate refugees might ultimately become residents. These converging maladaptations are now forcing us to face new consequences.

If the 'doughnut economy' or a similar alternative is not implemented, as is likely to be the case in a *just-too-late* global economic and political mode, the result will not be as these contemporary thinkers have envisioned, despite the predicted crucial C reduction targets of climate scientists, and it will take much longer than 2050 to reach net zero C+ emissions. Nevertheless, we all need to recognise eventually, but hopefully very quickly, that human societies can no longer operate in a global economy that is mainly disarticulated from our natural environment and the ecological services it provides (Pearce et al., 1989; Young, 1992; Hynes & Panetta, 1994).

One is tempted to feel some despair that 2022 marks the 50th anniversary of *The Limits to Growth* and that more than 30 years have passed since Pearce et al.'s *Blueprint for a Green Economy*. Yet, those of us who understand the significance of these authors' warnings must soldier on. Queensland and our nation need to play a realistic leadership role in this transformation. We have been slow learners in recognising the serious limitations of our current economic system in effectively managing the present and increasing environmental crises. It is time for change! *Fortis fortuna adiuvat!*

[d] With perhaps the exceptions being Paul Ehrlich's 1968 book *The Population Bomb* and Meadow's et al.'s 1972 *The Limits to Growth*.

Acknowledgements

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The Royal Society of Queensland
Annual Report 2021–2022

Overview

This report covers the period from 1 November 2021 to 31 October 2022.

The work program has been less intensive than in the previous year. Uncertain, changing restrictions on personnel movements on account of COVID-19 have discouraged the Society from attempting to convene face-to-face meetings, and a significant proposed event was cancelled for want of registrations.

Just as Council reported last year, the Society remains in precarious financial health. The plainest evidence is that it has not been able to meet the cost of typesetting or printing the 2022 *Proceedings* without substantial anonymous donations.

Corporate Affairs

The Royal Society of Queensland Council

The Council elected at the Annual General Meeting on 9 December 2021 comprised **Dr Ross Hynes** as President, **Dr Peter Dart**, **Dr Heather Douglas**, **Dr Geoff Edwards** as Vice-President, Policy, **Andy Grodecki**, **James Hansen** as Secretary, **Ben Lodge** (until 30 September), **Col Lynam**, and **Dr Joseph McDowall** as Treasurer.

Honorary Editor 2021, **Assoc. Prof. Julien Louys** of Griffith University, moved to Associate Editor role for 2022, and **Trevor Love** did not nominate for re-election.

Dr Justyna Miszkiewicz of University of Queensland took on the position of Honorary Editor, responsible for the annual issue, Volume 131, of the *Proceedings*, with support from **Assoc. Prof. Julien Louys**. After manuscripts for Volume 131 closed, Assoc. Prof. Louys agreed to take on the role of Honorary Editor for 2023 with Dr Miszkiewicz as Associate Editor.

Ben Lodge was appointed as Rangelands Coordinator but resigned as from 30 September 2022.

Tony Van Der Ark transferred Membership Coordinator duties to Treasurer **Dr Joseph McDowall** after 30 June, but **Dr Anne-Marie Smit**, who retired as Royal Society Newsletter Coordinator, has not been replaced. **Col Lynam** continued as Editor of the Queensland Science Network Newsletter. **Ms Shannon Robinson**, Queensland Museum's Librarian, continued in her role as the Society's Honorary Librarian.

Council Zoom meetings were held on 25 November 2021, 24 February 2022, 24 March, 26 May, 22 September and 20 October 2022. Face-to-face meetings of Council with Zoom facilities were held on 7 December (special meeting regarding Research Fund awards), the AGM on 9 December 2021 and a Strategic Planning meeting on 18 June. The majority of issues are debated via email traffic, telephone and Zoom.

During the year, the continued engagement of **Mrs Pam Lauder** as part-time (2–3 hours per week) Administration Coordinator and **John Tennock** on a retainer as Webmaster for both the Society's website and the Queensland Science Network (QSN) website have maintained the Society's administrative capacity.

Strategic Planning

At a face-to-face meeting held on 18 June and open to members, there was a wide consensus to broaden the scope of the Society's mission statement to remove the focus on the natural sciences and broaden the fields to include other scholarly disciplines. The provisional Mission Statement is:

> The Royal Society of Queensland – established in 1884 – is the State's senior scientific academy. The Society is a generalist learned organisation, seeking to uphold the standards of independent,

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evidence-led and curiosity-led enquiry. Its membership includes some of Queensland's most eminent researchers, as well as experts with senior policy experience, early-career researchers and laypeople with a general interest in the progress of knowledge. The Society speaks on behalf of a network of knowledgeable experts, bringing original knowledge to the notice of government, business, civil society, academia and the general public.

The Society provides platforms for thoughtful people committed to sharing and generating knowledge to conduct activities and publish their findings through both peer-reviewed and semi-popular web-based outlets.

A draft Strategic Plan is to be completed and available for further review by the end of 2022.

Finances

Having exhausted its accumulated reserves during previous years, primarily to fund the publication of its *Proceedings*, the Society operated without any cash cushion (in its general account) and some special projects such as a consultancy to prepare a Rangelands prospectus and the first invoices for typesetting the regular *Proceedings* were funded by private donations by members of the Council. The office-bearers have been unsuccessful in securing significant general-purpose sponsorship.

On 7 and 8 April 2022, multiple attempts were made by scammers to access the Society's bank accounts and transfer money fraudulently to outside accounts. Several of these attempts failed because of protections built in by the Society and the bank, but one succeeded. The Treasurer and Secretary reported all this to authorities and to the bank as these transactions had been made without our knowledge and consent. All bank accounts were closed and new accounts opened. However, an amount of $6,970 extracted from the Research Fund has not been recovered and the bank has advised that although investigations are continuing, it is unlikely that this sum will be recovered.

Membership Roll

At 30 October 2022, the Society has 116 paid-up and honorary members, a worrisome reduction on last year's 132. There are eight Honorary Life Members: **Dr A. Bailey**, **Dr J. S. Jell**, **Dr J. O'Hagan**, **Ms C. Melzer**, **Prof. C. Rose**, **Mr Craig Walton** and **Prof. Dilwyn Griffiths**. On 18 June 2022, **Emeritus Professor Angela Arthington** accepted the offer of Life Membership, to be invested at a date to be determined.

Events

Members' Online Forums

A series of informal forums, instituted on 21 October 2021 with a forum on science integrity, was continued on Tuesday evenings, to allow members to share knowledge about topics of interest to them. Forums were held on the following topics: the prospect of investing Fellows (**Dr Ross Hynes**), coal seam gas (**Dr Peter Dart and Col Lynam**), seismology (**Col Lynam**) and cyber security (**Ben Scott**). Two were open to the public. We thank all presenters for volunteering. The series was then placed in abeyance as no other members apart from Councillors volunteered to present and the numbers participating did not seem to justify the workload involved in planning the events.

Gatton Careers Workshop

On 11 August 2022, the Society presented to a seminar at Gatton College in a series on career planning for Gatton students, organised by The University of Queensland Wildlife Association. **Dr Peter Dart** as lead presenter attended in person, and **Dr Ross Hynes**, **Dr Geoff Edwards** and **Col Lynam** (from London) attended online.

Early-career Researchers

On 18 February 2022, an online event ably MCed by **Dr Justyna Miszkiewicz** featured impressive short presentations from early-career researchers and feedback from experienced scientists in the audience. Abstracts of several of the presentations have been published in the *Proceedings*. Strong interest was registered by early-career researchers.

Cancelled Event

An event proposed for 28 September in the Queensland Conservatorium to celebrate a philanthropic award of AU$10,000 for outstanding writers on social change was cancelled, with great regret on the part of the President and Council. After more than four weeks' advertising, only two attendees other than Council members had registered.

This was intended to be a novel and enterprising event co-hosted with the Royal Societies of Australia, and squarely involving the Society in the social sciences. The Society extends its apologies to **Dr Bruce Piasecki** and **Andrea Masters**, sponsors of the 'Award for Business and Society Writing', and to **Mr John Hardie**, President of the Royal Societies in Australia, that Brisbane was not able to fulfil the promise of this event.

Awards

We celebrate the specific achievements of members who have warranted external recognition:

- **Harry Van Der Ark –** Accepted to study at Columbia University, USA, with Prof. Brian Greene. December 2021.
- **Dr Heather Douglas –** Outstanding Reviewer Certificate from Emerald Publishing. December 2021.
- **Dr Justyna Miszkiewicz –** Martin & Temminck Fellowship, Naturalis Biodiversity Center, Netherlands, in September 2022 to research bone physiology in dwarfed insular mammals.
- **Emeritus Professor Angela Arthington** took on the eminent role of Specialty Chief Editor in the journal *Frontiers of Environmental Science – Freshwater Science*.

Publications

Proceedings of The Royal Society of Queensland

The annual issue of the *Proceedings of The Royal Society of Queensland*, Volume 129, was completed on time and printed in January 2022. Given that all articles are now available free of charge online, a reduction in the cost of printing presentation copies (for Her Excellency our Patron's library, statutory deposits, etc.) was expected. However, a decision to give free copies to all authors and the non-linear nature of printing costs meant that little was saved.

A Special Issue on *Preventative Health* has been foreshadowed but will be delayed. Volume 131, the 2022 annual issue, is on track to be completed and printed by the end of the year. At the date of completing this report, some eight substantive research articles had already been published online, with another seven abstracts of presentations made to the Early-career Researchers' event held in February 2022.

Newsletters

Ten Members' Newsletters were produced during the reporting period, against a target of monthly. These Newsletters are privileged to members. Newsletters are available on a members-only section of the website. The software reports that only about half of the members open their Newsletter e-mail.

Newsletters for the Queensland Science Network were paused after the eighth issue in October 2021. The Newsletter Editor, Col Lynam, has subsequently preferred to develop LinkedIn as the primary vehicle for disseminating information about general science. During the year, the LinkedIn network audience was built from two digits to more than 290. This has demonstrated the potential value of social media as a vehicle for disseminating knowledge about science and the Society's activities, as an alternative to traditional methods.

Occasional Papers

Council resolved to open a line of peer-reviewed 'Occasional papers' for scholarly-type articles that did not fit the format that made them eligible for the annual *Proceedings* or were outside its scope. Council had in mind, in particular, the half-dozen long papers written for the Rangelands initiative in October 2020. By 30 October 2022 no papers had finished navigating the editorial process. The primary reason is that authors, editors and referees have been too busy with other projects.

Press

On 17 November 2021, *The Mandarin* online newsletter published a column by **Dr Philippa England**, "Pay Farmers For Green Actions, Not For Obeying The Law" in its premium category.

In March 2022, a message advertising the availability of the Queensland Science Network as a teaching resource was included in the Department of Education's regular newsletter to its teaching fraternity.

The irreversible damage that mining for coal seam gas can wreak on cropping land through subsidence was a highlight of a scientific paper published in the *Proceedings* by four members.

The ABC gave an account of this threat in a news piece published on 8 October 2022, as did *Queensland Country Life* on 10–11 October.

Education Project

No progress was made during the year on development of new materials for the senior Queensland science curriculum as no funding was secured.

Rangelands Policy Dialogue

The Rangelands Policy Dialogue launched in July 2019 was paused at the end of December 2020. At the end of the reporting year no funds had been secured to allow this Dialogue to be given the organisational support that it warrants, and the Dialogue remains in limbo.

The Royal Society of Queensland Websites

During the year, the Society added the archive of the Queensland STEM Environment Network to its QSN website and has now added the domain www.queenslandstem.au with the agency of member and Syllabus Coordinator **Kay Lembo**. Domains controlled by the Society are now:

www.royalsocietyqld.org
www.royalsocietyqld.org.au
www.scienceqld.org
www.scienceqld.org.au
www.policyqld.org.au
www.rangelandsqld.org.au
www.queenslandstem.au

During the year, the Society declined to take up an offer by the domain registration authorities to register the first six of the above domains as ".au" without the ".org". Council judged that the risk of being held to blackmail by domain harvesters was low.

Research Fund

This year, some 21 applications were received for the fourth round of the Research Fund, for which $5000 was allocated. This is more than double the previously highest number and reflects extensive advertising by our Administration Coordinator **Pam Lauder** and Research Coordinator **Col Lynam**.

Col Lynam convened an assessment panel that included **Dr Heather Douglas** and **Dr Alistair Melzer** and presented the emerging conclusions to Council on 7 December.

In light of the large number of worthy applications, the President **Dr Ross Hynes** personally made an additional donation to allow a second grant. Then Council decided to allocate funds from the bequest of the late Professor Trevor Clifford supplied by the generosity of his family via family member and Society member **Kate Charters**. This allowed funding of two botanically oriented projects as well.

Four awards were made from a magnificent set of applications.

The recipients of the Trevor Clifford Bequest were:

- **Cassandra Rowe**, *Mua Island Garden Project* in Western Torres Strait, to enable her to visit the garden sites and undertake the appropriate field work and interact with people in Torres Strait; and
- **Dr David Nielsen**, *Queensland's Gardener: Walter Hill* who was responsible for setting up the Botanic Gardens and original collections of many Queensland species, to research the establishment of the Brisbane Botanic Gardens and associated collections.

The recipients of the Round 4 awards were:

- **Alexandria Mattinson**, looking at a specific disease of bananas: identification of novel peptides in Cavendish bananas during fusarium wilt infection, a horticultural biological disease-oriented project which is very relevant to Queensland and major banana producers of the world; and
- **Dr Tobias Smith**, assessing the distribution and conservation status of Australia's rarest stingless bee, *Tetragonula davenporti*.

Council agreed in principle to allocate $5000 for a fresh round in 2022, but at year's end had not appointed a Research Coordinator.

Final Words

The momentum of the Society's activities has been lower in the reporting year. Initiatives that are paused or proceeding at a slow rate of progress include:

- Rangelands Policy Dialogue

- Queensland curriculum materials
- Research Fund
- Monthly online forums
- Uploading fresh material to the Society, QSN and Rangelands websites
- Members' Interests page and networking
- Recruitment of members and retention of existing members
- Preventative health
- Royal Society and QSN Newsletters
- Survey of members to identify their interests and their willingness to contribute to the Society's work program.

Emphatically, this slower momentum does not apply to the publication of the annual *Proceedings*, and Council records its immense gratitude to the Honorary Editor and Associate Editor for bringing a most excellent volume to online near-completion.

The President, Vice-President, Policy, Dr Douglas and Ben Lodge have signified their intention to stand down from Council. This should allow new leaders to refresh Council and generate momentum to more actively fulfil its unique mission.

On behalf of all The Royal Society of Queensland members, I extend our thanks to all who have been involved and hope that the future will bring opportunities to restore and introduce more activities for our Society.

Ross Hynes
President
Date: 30 October 2022
On behalf of the Council

Hynes, R. A. (2022). The Royal Society of Queensland Annual Report 2021–2022. *Proceedings of The Royal Society of Queensland*, *131*, 171–175. https://doi.org/10.53060/prsq.2022-23

The Royal Society of Queensland
Award of Life Membership to Angela H. Arthington, 18 June 2022

The Society offers Life Membership to people either on account of their eminence in a professional discipline or their service to the Society. Emeritus Professor Angela Arthington unquestionably satisfies both criteria to a high degree. Having published in the *Proceedings of The Royal Society of Queensland* over five decades, first in 1975 and most recently in 2022, Angela's professional life has encapsulated the aim of the Society to uphold standards of scientific excellence.

The accompanying retrospective published in this volume summarises her career. Angela has built networks between disciplinary specialists, government and the community across the world of water. Just one example was the global release of the seminal publication *The Brisbane Declaration and Global Action Agenda on Environmental Flows* at the International Riversymposium meeting in 2017 in Brisbane where more than 1000 leaders gathered to share and discuss global water issues and river management. Linked to other activities, the declaration recognised the importance of humans within the water cycle and the necessity of improved monitoring of river health and biodiversity as a key indicator of the health of catchment and city water systems and societal well-being.

More recently Angela used her communication and networking skills in developing a book crossing jurisdictional and sectoral silos with her co-editing and coordinating the publication of the *Springs of the Great Artesian Basin*, a Special Issue of the *Proceedings of The Royal Society of Queensland*, in 2020. This volume saw research and management histories sourced from three states and written by a wide range of researchers, laypeople, lawyers and public servants. Angela successfully sourced funding from both Queensland and Commonwealth governments to publish the volume. To ensure that it received a wide release audience, she coordinated a workshop focused on the Basin springs within the Australasian Groundwater Conference held in Brisbane in 2019. She has subsequently spoken to a number of Queensland and national groups about the importance of conserving springs for their unique species and for their values to Indigenous people and society, as collated in the *Proceedings*.

Demonstrating her immense talents as a completer-finisher, in August 2022 Angela arranged

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for copies of the *Proceedings* to be provided to all members of the new national Great Artesian Basin Stakeholders' Advisory Committee at its inaugural meeting in Longreach, Queensland. Particularly useful to the group was a chapter in the *Proceedings* by Lynn Brake, a champion of the Great Artesian Basin from South Australia, that outlines a history of water extraction from the Basin from 1878–2020 and the significance of collaboration between landholders, experts, community groups and governments in the journey towards sustainability. An obituary and the negotiations that Angela conducted with Lynn Brake's widow over the volume's dedication to Lynn are testament to another of her talents, her compassionate spirit.

To produce one such compilation during a career is a praiseworthy achievement. But "Springs" comes eleven years after Angela served as lead editor of the 501-page *A Place of Sandhills: Ecology, Hydrogeomorphology and Management of Queensland's Dune Islands*, Volume 117, which remains a benchmark publication on Queensland's sand islands.

As if the above highlights and the long list of achievements chronicled in her retrospective were not sufficient achievement, in 2018 she allowed herself to be elected to serve on the Council of the Society, a post she held for three years while concurrently editing the annual Volume 128 of the *Proceedings* as well as the "Springs" Special Issue. As a Councillor she was meticulous in reading and editing documents, giving generous praise to others' contributions and giving well-grounded advice on complex matters. She retired from the Council position only to take up a prestigious sectional editorship of an international journal. Not just the Society and Queensland science but international science owe an enormous debt to Professor Angela Arthington; and as much as the Society honours her, we are honoured to count her as a Life Member.

Craig Walton
Ross Hynes
Geoff Edwards
On behalf of the Council of the Society

Council of The Royal Society of Queensland. (2022). The Royal Society of Queensland, award of life membership to Angela Arthington, 18 June 2022. *Proceedings of The Royal Society of Queensland*, *131*, 177–178. https://doi.org/10.53060/prsq.2022-21

A Career Retrospective

Angela H. Arthington

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Arthington, A. H. (2022). A career retrospective. *Proceedings of The Royal Society of Queensland*, *131*, 179–195. https://doi.org/10.53060/prsq.2022-22

This career retrospective supports the Award of Life Membership to Angela Arthington (Council of The Royal Society of Queensland, 2022).

Angela's early years were spent in Mt Gambier and Adelaide, South Australia, and later Rotorua and Christchurch, New Zealand, all places where her father held various positions as a forester. She attended the Whakarewarewa Māori School and Rotorua High School before the family moved to Christchurch and another rewarding role for their father with the New Zealand Forest Service. She completed the New Zealand School Certificate and University Entrance at Christchurch Girls High School, followed by a BSc Degree with First Class Honours at the University of Canterbury, majoring in zoology, with chemistry, botany and philosophy as subsidiary subjects. Encouraged by her favourite lecturer, a Canadian entomologist, she applied for PhD scholarship funding at MacDonald College of McGill University, Montreal, and completed her PhD in entomology and ecology by oral examination and thesis in 1969. A special feature of the PhD graduation process was giving a research presentation to the examining professors, who then took the candidate out to a sumptuous lunch in Sainte-Anne-de-Bellevue, a small town located at the western tip of the Island of Montreal in southwestern Quebec, Canada.

Four years of superb research training in insect taxonomy, morphology, pest management and general ecology led to a lectureship in the Entomology Department, University of Queensland, Brisbane, in 1970. Angela established student field classes in the dry sclerophyll ('wallum') forests, patterned fen wetlands and dune lakes of North Stradbroke Island, known as Minjerribah by its traditional owners, the Quandamooka People. Crossing to the island involved backing a university Land Rover down two narrow metal ramps onto an antiquated barge, watched by contingents of fishermen already well into their eskies full of stubbies, in high spirits and eager to see how a 'sheila' managed this tricky feat. Surveys of benthic, littoral and planktonic invertebrates and limnological data from Brown Lake and Blue Lake led to her first scientific paper (Bensink & Burton, 1975) published by The Royal Society of Queensland as part of a special issue on Stradbroke Island as a place for teaching.

Further studies established the unique features of oligotrophic sand dune lakes and their specialised biota, which included several species new to science (a primitive freshwater worm (*Rhizodrilus arthingtonae*), two dragonflies and several species of Trichoptera (caddisflies); one is named *Westriplectes angelae*). New distribution records for freshwater fishes, *Pseudomugil mellis* and *Nannoperca oxleyana*, and an assessment of threats to their habitats, led to IUCN and Australian 'Threatened' species listings and the development of species recovery plans (Knight et al., 2012). These early findings informed another special issue of The Royal Society of Queensland *Proceedings*: *A Place of Sandhills: Ecology, Hydrogeomorphology and Management*

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of Queensland's Dune Islands (Arthington et al., 2011; Hadwen & Arthington, 2011). Freshwater biodiversity discoveries and ecological insights helped to prevent sandmining on Moreton and Fraser Island and contributed to the World Heritage listing of Fraser Island and the Cooloola Sand Mass in 1992.

Angela joined the School of Australian Environmental Studies at Griffith University, Brisbane, in 1975, and it has been her academic home ever since. As well as establishing undergraduate courses in freshwater ecology, she soon began new lines of research on the ecology of urban streams. Her first project was focused on the development of biological indicators to assess effects of organic pollution on polluted Bulimba Creek. Invertebrate diversity, and patterns of association between pollution gradients and the distribution of dragonfly species that breed only in running waters (e.g. *Austroepigomphus praeruptus*) and remain close to oviposition habitat (Watson et al., 1982), were deemed useful pollution indicators. An invitation to explore the incidence and implications of alien fishes in South East Queensland waterways gave rise to studies on the ecology and impacts of the mosquitofish (*Gambusia holbrooki*) and the cichlid (*Oreochromis mossambicus*, the Mozambique mouthbrooder) in particular. Collaboration with the Curator of Fishes at the Queensland Museum was inspiring, and a string of publications followed (e.g. Arthington et al., 1983). The highlight of this period was a meeting of the Global Invasive Species Program (GISP) Expert Consultation (2003) held at the Smithsonian Institute in Washington DC, and a 'white paper' on the global problems of alien cichlid (tilapia) species in freshwater systems (Canonico et al., 2005).

Another milestone was establishment of the Centre for Catchment and In-Stream Research (CCISR), one of 12 Centres of Concentration established in 1987 by the Australian Water Research Advisory Council (AWRAC), Department of Primary Industry, Canberra. CCISR was funded initially by a five-year grant to develop freshwater biodiversity and river basin studies, drawing upon the expertise of faculty members and new appointees. Eminent Griffith University colleagues joined CCISR and one wit said that our major theme should be research 'at the cutting edge' of freshwater science. This was prophetic. Supported by numerous research grants, commissioned projects and postgraduate research, CCISR's research program soon diversified and morphed into the globally prominent Australian Rivers Institute (ARI) of today. Leading CCSIR for five years was a challenge and a profound honour.

Research on the ecological water requirements (environmental flows, also known as e-flows) of freshwater species became the central theme of Angela's research from the 1990s, starting with the effects of a new dam on Barker-Barambah Creek near Murgon, a study funded by the Queensland Water Commission. Further investigations on fish communities and flow regimes of Queensland's major coastal rivers were supported by the Land and Water Resources Research and Development Corporation (LWRRDC), the Rainforest Cooperative Research Centre (CRC) and the Queensland Government, producing a mass of basic data on the habitat requirements and ecology of 79 freshwater fish species. In 2004, Brad Pusey, Mark Kennard and Angela assembled this information and related literature in *Freshwater Fishes of North-Eastern Australia* (Pusey et al., 2004). This volume won the 2005 Whitley Medal, awarded annually since 1979 by the Royal Zoological Society of New South Wales to commemorate Gilbert Whitley (1903–1975), an eminent Australian ichthyologist. Whitley awards celebrate publication of the best books containing new information about the natural history of the fauna of the Australasian region. Presentation ceremonies are wonderful events held at the Australian Museum in Sydney where a prominent scientist reads the nomination and applauds each book's achievements. The medal itself is beautiful.

Research on fish ecology in floodplain rivers continued via projects with the Rainforest CRC and the Marine and Tropical Sciences Research Facility (MTSRF), a 4-year $40m component of the Commonwealth's Environment Research Facilities program. A fruitful collaboration with colleagues from James Cook University and CSIRO led to a suite of publications and an associated PhD program on floodplain rivers of the Wet Tropics (Arthington et al., 2015; Godfrey et al., 2017, 2022; Pearson et al., 2013) and new models of floodplain connectivity (Karim et al., 2012, 2014). These studies helped to drive new policy directives for the protection and restoration of interconnected catchment, riverine, floodplain and estuarine systems, as part of the

Great Barrier Reef 2050 Long-Term Sustainability Plan 2018, an overarching strategy for managing the GBR over the next 30 years (Arthington et al., 2020a). Angela is presently contributing freshwater science perspectives into the 2022 Scientific Consensus Statement (SCS) on land-based water quality impacts on the Great Barrier Reef.

Moving away from coastal rivers in 2005, Angela joined the 'Dryland Refugium Project' funded by the Freshwater CRC to research patterns of fish diversity and recruitment in floodplain rivers of the Lake Eyre Basin (LEB). This period of research in the remarkable river systems of Australia's arid interior produced new insights into the community ecology and 'boom and bust' dynamics of fish species adapted to long periods of aridity punctuated by extensive floods (Arthington & Balcombe, 2011). Angela has applied this information as a member of the Scientific Advisory Panel for the LEB, currently focused on a review of the Lake Eyre Basin Rivers Assessment (LEBRA) and development of new indicators to measure emerging threats to arid-zone rivers and their endemic species. One of the most threatened species is the Cooper Creek catfish, *Neosiluroides cooperensis*, now listed as endangered on the IUCN Red List of Threatened Species (Arthington et al., 2019).

Springs of the Great Artesian Basin (GAB) became another research interest when working with the Commonwealth's Independent Expert Scientific Committee (IESC) on Coal Seam Gas and Large Coal Mining Development. Seeing the need for a compendium of recent scientific and management information, Angela and a team of editors produced *Springs of the Great Artesian Basin*, a Special Issue of the *Proceedings of The Royal Society of Queensland* published in 2020. This volume of 19 papers gives easy access to interesting and compelling information about GAB springs, which are biodiversity havens for many rare and endemic species. One of them is the critically endangered red-finned blue-eye (*Scaturiginichthys vermeilipinnis*) found only in Edgbaston (*Byarri*) Springs. Papers in this volume record the passion of Indigenous Peoples, pastoralists, scientists, governments and conservation groups working together to improve stewardship of spring ecosystems and their supporting aquifers (Arthington et al., 2020b; Rossini et al., 2020).

Angela's ongoing river ecology and fish research has contributed to several novel frameworks for assessing the environmental flow requirements of riverine biota. Collaboration with river scientists from South Africa led to wonderful field work in rivers of the Lesotho Highlands, and development of the e-flows framework known as DRIFT (Downstream Response to Imposed Flow Transformation) and its fish component (Arthington et al., 2003). Several years of international collaboration also produced a precursor paper and eventually the multi-faceted e-flows framework known as ELOHA (Ecological Limits of Hydrologic Alteration) (Arthington et al., 2006; Poff et al., 2010). Numerous publications and practical experiences with e-flow studies and recommendations for Queensland's coastal rivers culminated in the book *Environmental Flows: Saving Rivers in the Third Millennium* (University of California Press, 2012), since translated into Chinese. Angela was honoured to receive the 'Making a Difference Award' from the US Instream Flow Council during their annual Flows Conference held in Portland in 2015. In his presentation speech the conference President recommended a single paper (Bunn & Arthington, 2002) as an absolute "must read" for anyone interested in environmental flows; that paper has clocked up 4036 citations (Google Scholar, 29 October 2022). Another highly cited publication (Dudgeon et al., 2006) arose from meetings of the freshwaterBIODIVERSITY program of DIVERSITAS, aimed at developing a new global science agenda for biodiversity in support of sustainable freshwater ecosystems and human well-being. This seminal paper on freshwater biodiversity values and threats has been cited in 6773 subsequent publications (Google Scholar, 29 October 2022).

In 2018 Angela led the compilation and publication of the *Brisbane Declaration and Global Action Agenda on Environmental Flows*, a status review and call for action to protect the dynamic flow regimes and freshwater biodiversity of the world's rivers and wetlands (Arthington et al., 2018). A renewed definition of environmental flows and some elements of the associated Global Action Agenda have been taken up by the Food and Agriculture Organization (FAO), as custodian UN agency for Sustainable Development Goal Indicator 6.4.2

'level of water stress: freshwater withdrawal as a proportion of available freshwater resources'. Accelerated implementation of e-flows also forms part of an Emergency Recovery Plan to "bend the curve" of freshwater biodiversity loss towards recovery and protection (Tickner et al., 2020). This plan's 6-point action agenda is explicitly aligned with the goals and indicators of the emerging Post-2020 Global Biodiversity Framework and its mission to 'Halt the loss of species, ecosystems and genetic diversity by 2030; restore and recover biodiversity to ensure a world of people "living in harmony with nature" by 2050'.

During her career Angela has supervised 20 Honours, Masters and PhD candidates, written/edited four books, edited four journal special issues and published over 300 papers, book chapters and research/consultancy reports (h-index 73). Her efforts have brought $9m into the Griffith University's research budget since 1980. She has served on many advisory panels, including the Australian Water Research Advisory Council (AWRAC), the Land and Water Resources Research and Development Corporation (LWRRDC), Land and Water Australia, the DIVERSITAS Freshwater Cross-cutting Network, the Environmental Water Scientific Advisory Panel (EWSAP) (advising the Commonwealth Environmental Water Holder), the LEB Scientific Advisory Panel (SAP) and the Commonwealth's Independent Expert Scientific Committee (IESC) on Coal Seam Gas and Large Coal Mining Development. Her achievements in research, education, leadership and management of freshwater biodiversity have been recognised by her inclusion in the 2015 Hall of Fame of the Australian Society for Fish Biology (ASFB), and by the award of the 2018 Australian Society for Limnology (ASL) Medal for outstanding contributions to Australian freshwater science. Another highly valued honour was giving the 19th Annual H.B.N. Hynes Lecture in 2020 entitled *Progress with Environmental Flows to Maintain Healthy Rivers and Healthy Societies* (Figure 1). The Canadian Rivers Institute initiated its annual lecture series in 2002 by the conferring of an Honorary Doctoral Degree to Dr H. B. N. Hynes (1917–2009). As the world's most renowned freshwater biologist and 'the father of running water ecology', Professor Hynes was a role model for many river scientists, and his definitive textbook on river ecology, *The Ecology of Running Waters* (2001), remains inspiring.

FIGURE 1. Advertising Angela Arthington's 19th Annual H.B.N. Hynes 2020 Lecture (reproduced with permission from The Canadian Rivers Institute).

Angela is now working as an Adjunct Emeritus Professor in the Australian Rivers Institute at Griffith University, writing, editing and reviewing for many journals. She is an editor of the journal *Aquatic Conservation: Marine and Freshwater Ecosystems* and currently holds the position of Specialty Chief Editor of *Frontiers in Environmental Science – Freshwater Science*. The journal's broad statement of scope, highlighted in her 'Grand challenges' paper (Arthington, 2021), offers many opportunities to publish freshwater science and promote the conservation of freshwater biodiversity in our changing world.

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