Received: 30 November 2020 | Accepted: 31 March 2021
DOI: 10.1111/1365-2664.13897

RESEARCH ARTICLE

Journal of Applied Ecology BRITISH ECOLOGICAL SOCIETY

Rock removal associated with agricultural intensification will exacerbate the loss of reptile diversity

Damian R. Michael[1] | Harry Moore[1] | Skye Wassens[1] | Michael D. Craig[2,3] | Reid Tingley[4] | David G. Chapple[4] | Jackie O'Sullivan[5] | Richard J. Hobbs[2] | Dale G. Nimmo[1]

[1]Institute for Land, Water and Society, Charles Sturt University, Albury, NSW, Australia

[2]School of Biological Sciences, The University of Western Australia, Crawley, WA, Australia

[3]Environmental and Conservation Sciences, Murdoch University, Murdoch, WA, Australia

[4]School of Biological Sciences, Monash University, Clayton, Vic., Australia

[5]Fenner School of Environment and Society, The Australian National University, Canberra, ACT, Australia

Correspondence
Damian R. Michael
Email: dmichael@csu.edu.au

Handling Editor: Tien Ming Lee

Abstract

1. Rocky environments host rich levels of biodiversity and provide vital habitat for specialised organisms, range-restricted species and a broad range of ectotherms adapted to saxicoline environments.
2. In Australia, rock habitat is being destroyed during soil amelioration practices associated with agricultural intensification. Advances in rock crushing technology, developed to expand or increase crop yields and efficiency, pose an undocumented threat to global biodiversity, especially reptiles dependent on non-renewable rock habitat in agricultural landscapes. Rock removal is a legislated key threatening process in parts of Australia and will accelerate biodiversity loss if not mitigated.
3. We estimated reptile species' range overlap with dryland cropping and modified pastoral regions within the Australian wheat-sheep zone to assess the potential impacts of rock crushing practices. We examined species- and family-richness within the impact zone and across bioregions within the impact zone, to identify areas where rock removal has the greatest potential to impact terrestrial and fossorial squamates.
4. Our analysis revealed that 159 potentially impacted reptile species occur within the study area, representing 16% of Australian terrestrial squamates. Fourteen of these species, including six threatened species, have more than 50% range overlap with areas of intensive agriculture, and include several endangered pygopodids, scincids and agamids.
5. Bioregions rich in rock and burrow-dwelling reptiles include the Brigalow Belt South, Murray Darling Depression, Darling Riverine Plains, Eyre Yorke Block, Avon Wheatbelt, Nandewar, Flinders Lofty Block and New South Wales South Western Slopes.
6. *Synthesis and applications*. The conservation of reptiles in agricultural landscapes requires appropriate management and retention of surface rocks. Potential yield increases from destroying rock habitat to intensify or expand cropland will not compensate for the net loss of reptile populations dependent on non-renewable resources. Financial incentives to prevent the expansion and transformation of

non-arable landscapes to cropland are required to prevent the ongoing loss of biodiversity.

KEYWORDS

agricultural intensification, bush rock, habitat degradation, habitat loss, land use change, rock crushing, rock removal, soil amelioration

1 | INTRODUCTION

Agricultural intensification is a key driver of biodiversity loss world-wide (Foley et al., 2005; Green et al., 2019; Sala et al., 2000; Tingley et al., 2019). As agriculture has become more mechanised in the last 150 years, the terrestrial biosphere is now increasingly dominated by anthropogenic activity (Ellis et al., 2010). During this period, 42%–68% of the Earth's land surface was impacted to some degree by cropping, grazing or timber harvesting (Hurtt et al., 2006), contributing to declines in reptiles (Böhm et al., 2013; Gibbons et al., 2000; Todd et al., 2010), insects, birds and mammals (Harris et al., 2009; Şekercioğlu et al., 2004; Thomas et al., 2004). Agricultural crop production is anticipated to double by 2050, driven by human population growth, food consumption, biofuel use and global crop exports (Godfray et al., 2010; Ray et al., 2012), placing further pressure on biodiversity world-wide (Ghosh & Basu, 2020).

Despite widespread land clearing, many native species persist in agricultural landscapes (Daily et al., 2003; Haslem & Bennett, 2008), especially terrestrial reptiles (Pulsford et al., 2018). Retaining native vegetation, and other natural features, is key for maintaining biodiversity in modified landscapes (Daily et al., 2001; Frishkoff et al., 2019). Rock outcrops provide one example of a keystone resource that provides refuge for specialised or range-restricted species (Fitzsimons & Michael, 2017; Mendenhall et al., 2011; Michael et al., 2015; Michael & Lindenmayer, 2018a; Speziale & Ezcurra, 2015). These types of habitats preserve functional diversity that is critical for maintaining biological processes, and for facilitating ecosystems services on which agricultural enterprises depend (Landis, 2017; Macfadyen et al., 2012). Surface rocks are also a dominant feature of cleared landscapes, providing habitat for specialised invertebrates (Pinder et al., 2000), reptiles (Michael et al., 2008) and plant communities (Anderson et al., 2007; Gibson et al., 2010). Rocks buffer against climate extremes and mitigate the impacts of fire or vegetation clearing by providing ectotherms with refuge, nesting sites and thermal gradients (Goldsbrough et al., 2006). However, many rocky environments are degraded by livestock grazing, weed invasion and rock removal (Burke, 2003; Michael et al., 2010). Despite these known threats, there is a paucity of studies on the ecological value of surface rocks in agricultural landscapes.

Australia provides a case study where recent advances in rock crushing machinery (Michael & Lindenmayer, 2018), developed to crush sheet rock and laterite soils, may exacerbate biodiversity loss by eliminating critical habitat from agricultural landscapes. Surface rock removal is a key threatening process in New South Wales (NSW; *NSW Biodiversity Conservation Act 2016*) and has been implicated in the decline in several grassland species, including the presumed extinct Victorian grassland earless dragon *Tympanocryptis pinguicolla* (Melville et al., 2019), yet the practice is permitted as part of routine agricultural activities. Technology that facilitates broad-scale conversion of non-arable land by crushing surface rock and cultivating intact soils (e.g. soil amelioration) is at odds with sustainable farming practices and will exacerbate biodiversity loss, especially species that are fossorial, have poor dispersal ability and are dependent on surface rocks or subterranean microhabitat, such as spider burrows and soil cracks.

The threat of rock crushing practices on biodiversity recently emerged in Australia (Michael, 2020; Michael & Lindenmayer, 2018b). However, the negative consequences of agricultural intensification are a well-documented global issue (de Graaff et al., 2019; Emmerson et al., 2016). Advances in rock crushing machinery that enables landholders to remove broad areas of surface rock from non-arable landscapes have the potential to rapidly increase the amount of intensively cultivated land world-wide. Thus, there is an urgent need to assess the potential impacts of rock removal and agricultural intensification to inform sustainable land management and conservation policy in agro-ecosystems. In this study, we highlight rock crushing practices as an emerging threat to biodiversity. We focus our analysis on reptiles as they are the most species-rich group of vertebrates dependent on surface rocks in agricultural landscapes (Nopper et al., 2017; Pulsford et al., 2018), and therefore serve as a suitable surrogate for other rock-dwelling organisms. To evaluate the potential impacts of this threat, we collated a comprehensive list of reptile species known to occur within intensively managed agricultural regions in Australia. To reflect habitat affiliations, we then classified species as obligate or generalist rock-dwellers, before estimating species' range overlap within the study area. Lastly, we identify specific taxa and bioregions potentially impacted by rock crushing practices. Our findings have broad implications for biodiversity conservation in agricultural landscapes world-wide.

2 | MATERIALS AND METHODS

2.1 | Study area

As we were primarily interested in the impacts of rock crushing technology, we confined our analyses to the dryland agricultural regions of Western Australia and south-eastern Australia (see Appendix S1 in Supporting Information), where this has become a common and widespread practice in recent years. These two regions are referred to as the

Australian wheat-sheep zone (WSZ) and cover 986,000 km^2. The WSZ is characterised by undulating hills, nutrient-poor soils and a seasonally wet/dry climate that ranges in eastern Australia from 300 mm in the south to 600 mm in the north, and in Western Australia from 600 mm in the south-west to 300 mm in the northern and eastern parts of the WSZ. The geology is complex and includes laterite ironstone formations in the west, limestone reefs in South Australia and basalt in the east and granites in the east and west. Within the WSZ, primary land use for cropping or modified pasture grazing was defined as the 'impact zone', where soil amelioration increasingly involves mechanical removal of surface rocks and small outcrops. To map the impact zone, we used data from the Australian Land Use and Management (ALUM) Classification version 8, rescaled to a resolution of 1 km × 1 km. Based on this dataset, the total area of land devoted to cropping and modified grazing within the WSZ was calculated as 318,547 km^2.

2.2 | Species assessment

We used reptile location records available in the Atlas of Living Australia database https://www.ala.org.au to derive a list of species that occur within dryland cropping and modified pasture zones based on the ALUM classification. Our list included species associated with surface rocks, low rocky outcrops and stony rises, or if agricultural intensification was explicitly listed as a threat in the IUCN Red List of Threatened Species database (IUCN, 2020). We also included species that use soil cracks and spider burrows (collectively termed burrow-dwellers), but excluded species associated with sandy soils and associated vegetation communities. Aquatic and arboreal species were also excluded, as were *Tympanocryptis pinguicolla* and *T. maccartneyi*, as the former is presumed extinct and the latter is only known from three records from the township of Bathurst (Melville et al., 2019) and overlap with the impact zone is unknown.

2.3 | Geographical range analysis

To assess the potential impacts of rock crushing and soil amelioration on reptile species that met the aforementioned criteria, we estimated species' range overlap within the impact zone and conservation reserves for comparison, classifying species conservation status according to the IUCN (2020) or *Environment Protection and Biodiversity Conservation Act* (1999) (EN—endangered, VU—vulnerable, NT—near threatened, LC—least concern and DD—data deficient) and affiliation to rock habitat. Species that primarily shelter, breed or thermoregulate beneath surface rocks were classified as obligate rock-dwellers, whereas species that opportunistically shelter, breed or thermoregulate beneath rocks or use subterranean microhabitats were classified as generalists. Species range data were sourced from the IUCN database available from http://www.iucnredlist.org/. This database was vetted by Australian experts during a recent workshop (Chapple et al., 2019; Tingley et al., 2019). To identify biological hotspots, we first mapped total species richness and species richness of families within the impact zone, then calculated species richness within bioregions using the Interim Biogeographic Regionalisation for Australia (IBRA) system, which classifies geographically distinct bioregions based on common climate, geology, landform, native vegetation and species information (see Appendix S2 in Supporting Information).

3 | RESULTS

3.1 | Rock and burrow-dwelling species

We found 159 rock or burrow-dwelling species occur within the impact zone, representing 15.9% of Australian terrestrial squamates (Table 1). Species composition was dominated by the family Scincidae (44.7%), followed by Elapidae (12.4%), Pygopodidae (11.2%), Diplodactylidae (10.5%), Agamidae (10.5%), Typhlopidae (6.2%), Gekkonidae (3.1%) and Carphodactylidae (1.2%). Thirteen species are listed as threatened under IUCN Red List criteria or EPBC Act (1999; Table 1).

3.2 | Species' range overlap with impact zone

We found 64 species have more than 30% range overlap with the impact zone and 14 species have more than 50% range overlap,

TABLE 1 Number of rock or burrow-dwelling reptile species in dryland cropping and modified pastoral zones in Australia with this as a percentage of the Australian reptile fauna and including the number of threatened species (IUCN Red List and EPBC Act 1999)

Family	Number and percentage of species	IUCN	EPBC Act 1999	Total number of threatened species
Agamidae	18 (19.5)	2	1	2
Carphodactylidae	2 (6.3)	1	1	1
Diplodactylidae	17 (17.9)	1	—	1
Gekkonidae	5 (7.3)	—	—	0
Pygopodidae	18 (40.9)	2	4	5
Scincidae	72 (15.7)	2	3	4
Typhlopidae	10 (20.8)	—	—	0
Elapidae	20 (18.7)	—	—	0
Total	159 (15.9)	8	9	13

including six threatened species and two obligate rock-dependent species (Figure 1). Species with small geographical ranges that have high overlap with the impact zone and low overlap with conservation reserves include *Anilios pinguis* (LC), *Aprasia aurita* (NT), *A. parapulchella* (VU), *Ctenophorus adelaidensis* (LC), *Delma grayii* (LC), *D. impar* (EN), *D. molleri* (LC), *D. hebesa* (LC), *Egernia kingii* (LC), *Lampropholis elongata* (DD), *Lerista yuna* (NT), *Parasuta flagellum* (LC), *Tiliqua adelaidensis* (EN) and *Tympanocryptis condaminensis* (EN), and we consider these species to be the most imperilled from rock crushing (Figures 2 and 3).

3.3 | Species-rich bioregions and hotspots

Forty-five (50.5%) of IBRA bioregions in the study area support rock or burrow-dwelling reptiles. A core area supporting high reptile species richness occurs in an arc from South Australia extending east and north along the northern and western slopes of the Great Dividing Range (Figure 4). Among families, Australian states that support high numbers of rock-dwelling species include South Australia (Agamids), Western Australia and South Australia (Gekkonids), northern NSW (Typhlopids), Western Australia and South Australia (Elapids), and Western Australia and NSW (Pygopodids; Figure 5).

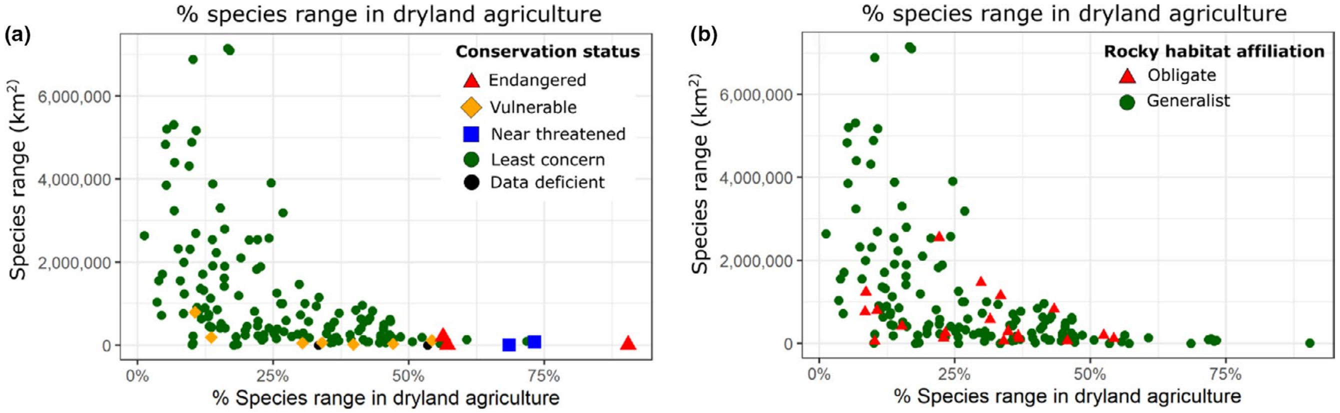

FIGURE 1 (a) Proportion of species' range overlap with the impact zone classified by conservation status, and (b) habitat affiliation. Species in the lower right-hand corner are likely most exposed to rock removal in dryland cropping and grazing regions, and species in upper left-hand corner are least likely to be at risk

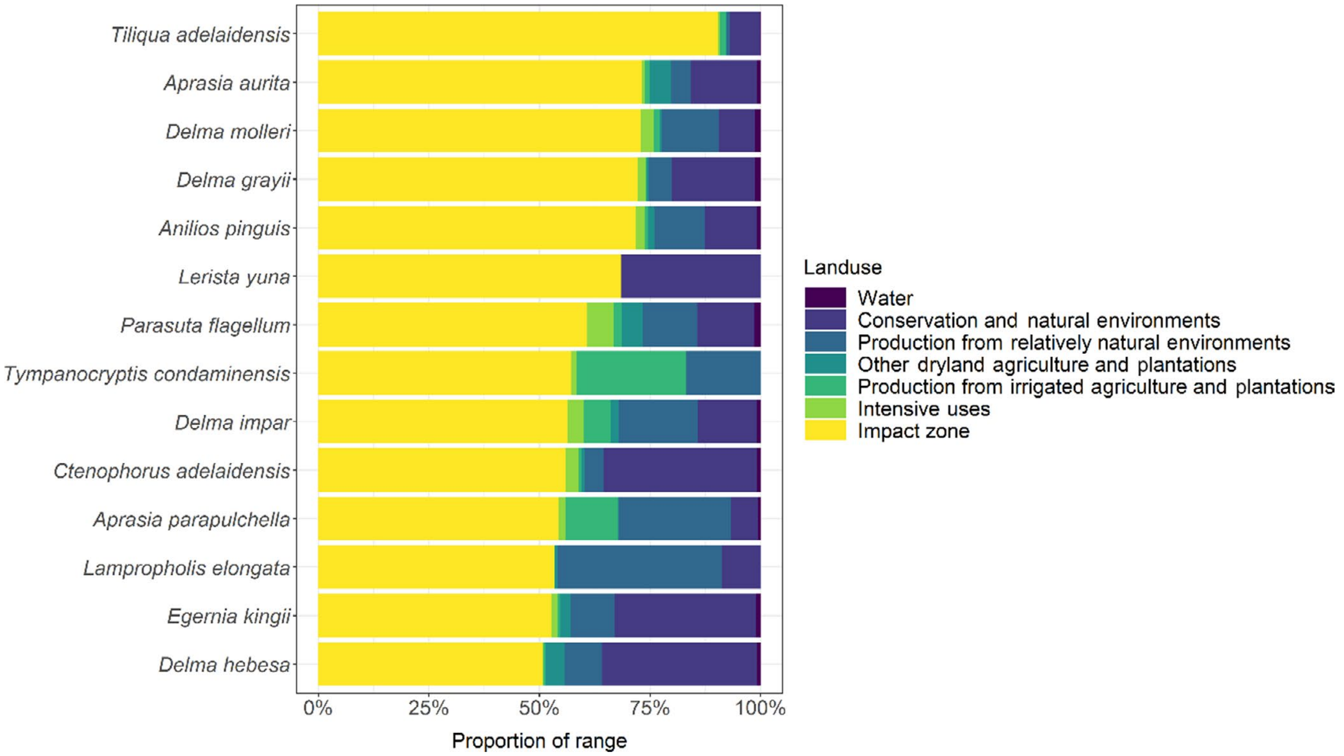

FIGURE 2 Proportion of range overlap with six land use types for 14 most imperilled rock or burrow-dwelling reptiles in the wheat-sheep belt of Australia

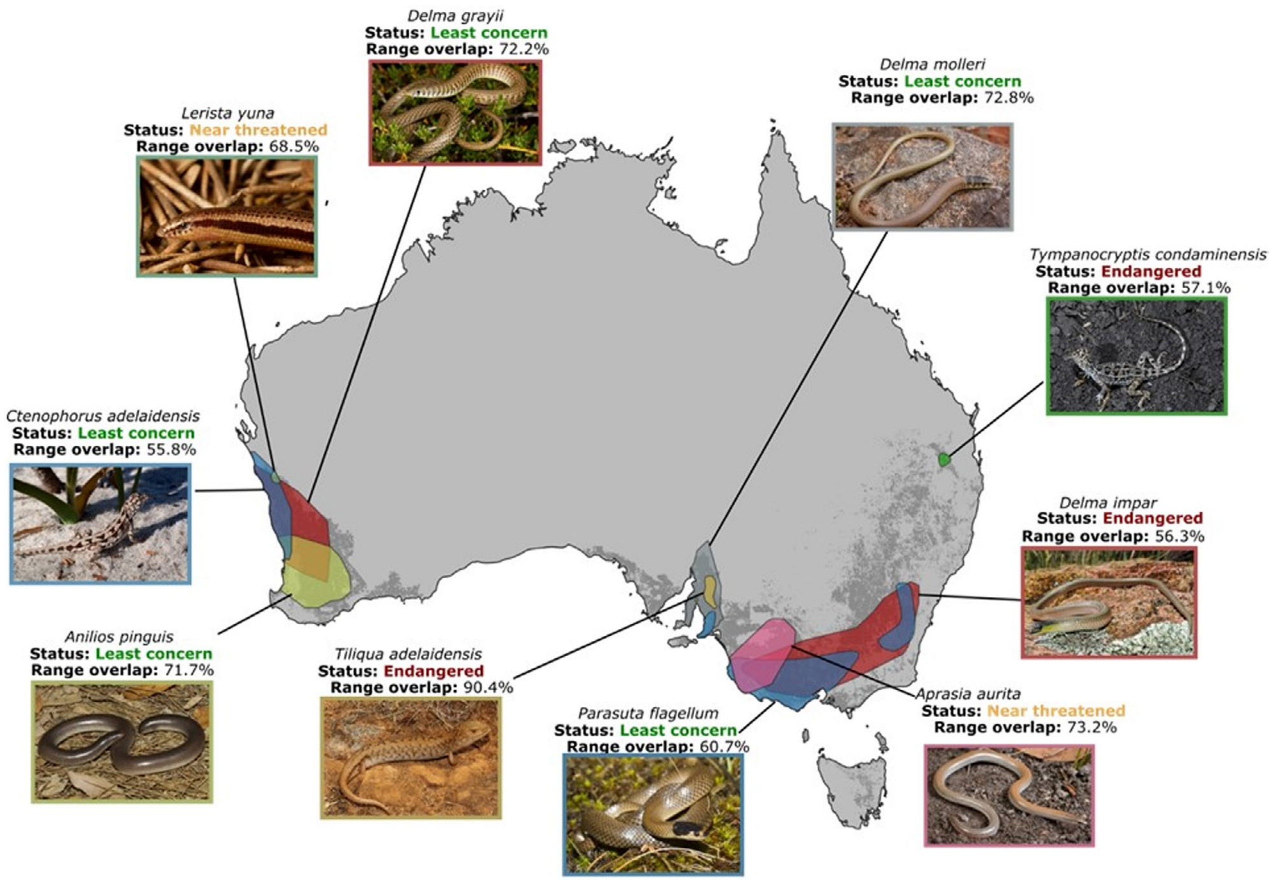

FIGURE 3 Geographical location of reptile species with high range overlap with dryland cropping and modified pastureland use zones in Australia

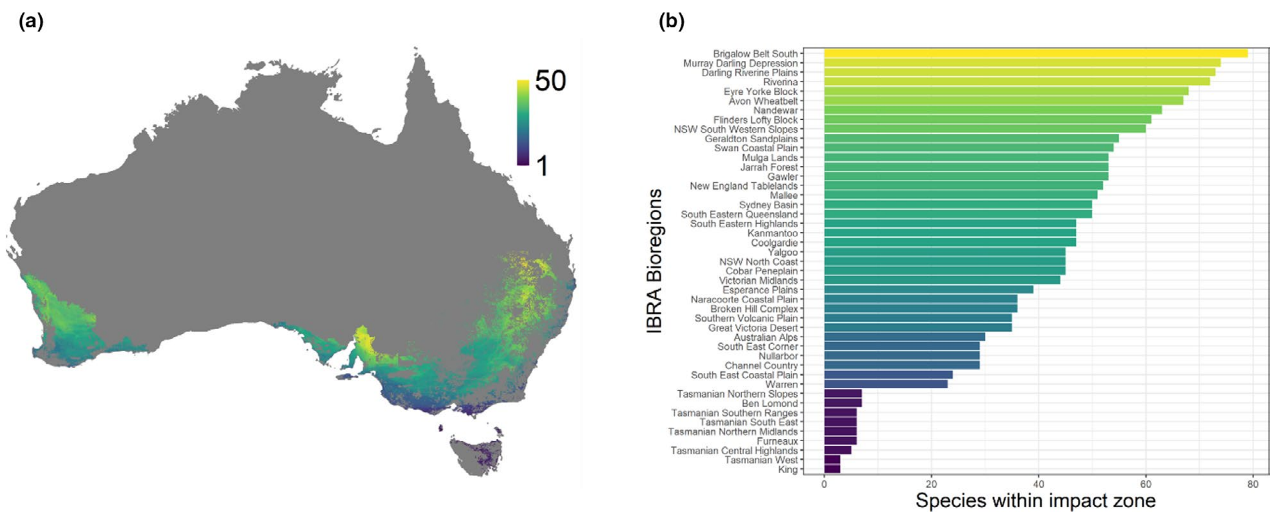

FIGURE 4 (a) Reptile species richness within the impact zone and (b) total species richness across IBRA bioregions (see Appendix S2 in Supporting Information)

4 | DISCUSSION

4.1 | Impact of rock crushing on reptiles

Agricultural intensification threatens biodiversity world-wide (Green et al., 2019; Tingley et al., 2019). Broad-scale rock removal associated with soil amelioration practices is an emerging aspect of agricultural intensification that has received little attention. Our assessment of the geographical range overlap of Australian rock and burrow-dwelling squamates within intensively managed agricultural regions highlights an emerging threat that could exacerbate biodiversity loss and underscores the importance of retaining rock habitat in agricultural

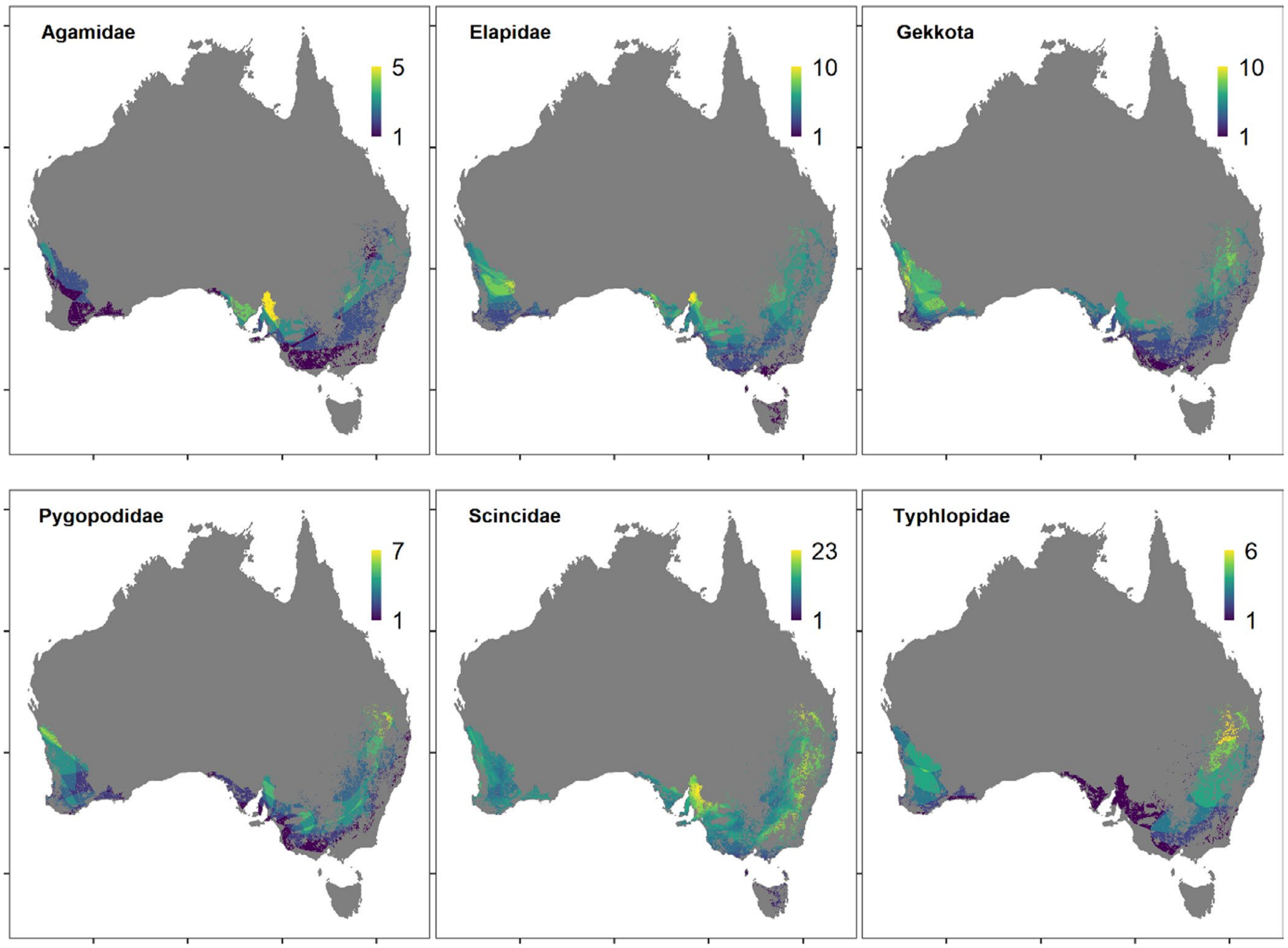

FIGURE 5 Reptile species richness maps for major taxonomic groups within the impact zone (Gekkota includes Gekkonidae, Diplodactylidae and Carphodactylidae)

landscapes. We identified 14 reptile species that have half of their global distribution within agricultural landscapes, most of which have relatively little of their range within conservation reserves. These most imperilled species include six species already listed under a threatened category (*Aprasia aurita*, *A. parapulchella*, *Delma impar*, *Tiliqua adelaidensis*, *Tympanocryptis condaminensis* and *Lerista yuna*). Many of these species are characterised as range restricted, fossorial, have poor dispersal ability and are dependent on rocks or burrows for survival. Some species such as *A. aurita* are relatively well-protected within conservation reserves, and others such as *D. grayii* are rock-dwelling generalists with flexible shelter requirements. However, broad-scale habitat loss across the WSZ means that many unknown populations on private land that are reliant on surface rocks are likely to be affected by rapidly expanding rock crushing practices.

Species-rich bioregions include the Brigalow Belt South, Murray-Darling Depression, Darling Riverine Plains, Eyre Yorke Block, Avon Wheatbelt, Nandewar, Flinders Lofty Block and NSW South Western Slopes. Our assessment of the potential impact of rock crushing on reptiles is likely to be conservative should the technology expand into uncultivated land use types such as native pasture. However, baseline data on the impact of rock removal from agricultural regions are lacking. It should also be noted that range maps may overestimate true distributions and so the extent to which species' ranges overlap with the impact zone or protected areas should be interpreted with caution (Tingley et al., 2019).

The practice of removing rocks from non-arable landscapes to establish crops is centuries old, but in some regions the impacts were partially offset by the construction of dry-stone walls and boundary rock fences. Such anthropogenic rock features dominate agro-environmental landscapes in Europe and parts of the United States (e.g. Kentucky Bluegrass and New England regions; Murray-Wooley & Raitz, 2015), where they have novel ecological, cultural and aesthetic values (Collier, 2013). The creation of rock piles and stone walls following past clearing of rocks from agricultural fields probably had similar effects in Australia, creating localised rather than dispersed rock habitats. However, the destruction and degradation of rock habitat has well-documented negative impacts on species dependent on rocks for shelter, ovideposition and thermoregulation (Goldingay & Newell, 2017; Pike et al., 2010; Shine et al., 1998), and it is likely that historical rock picking from across Australia's farmlands caused undocumented declines in reptiles. Rock crushing technology, designed specifically to crush rocks on non-arable ironstone country, has the capacity to convert rocks into gravel at a rate of 1 ha per hour. This practice signals concern for fossorial, low-vagility species dependent on rock microhabitat in agricultural landscapes, but also has broad implications for maintaining soil microbes and landscape processes (Emmerson et al., 2016).

Since early civilisation, certain periods are marred by landscape-scale changes to the environment, resulting in biotic homogenisation and shifts in ecosystem stability (Wang & Loreau, 2016). A wave of localised extinctions accompanied post-World War II soldier settlement schemes in Australia (Hobbs, 2003; Saunders, 1989) and the development of harvesting methods that enabled landholders to rapidly clear large tracts of native vegetation for broad-scale wheat and sheep production. The method at the time involved dragging a chain (often with a large steel sphere) through bushland with tractors or bulldozers (Harris et al., 2010). With less than 10% of native vegetation remaining across the Australian WSZs (Yates & Hobbs, 2000), rapid declines in biodiversity have already occurred (Ford et al., 2001; Hobbs & Saunders, 1991; Saunders, 1989). Advances in rock crushing machinery may trigger another wave of extinctions, especially if the technology is used in areas not already intensely cultivated. Soil amelioration practices are gaining popularity in Western Australia, South Australia, Victoria and New South Wales, and will inevitably be adopted in other countries seeking to establish crops in non-arable landscapes.

4.2 | Management and conservation implications

We highlight an emerging aspect of agricultural intensification that has the potential to impact a broad array of range-restricted and terrestrial reptiles that utilise rock and subterranean habitat in Australia's wheat-sheep belt for shelter, breeding and thermoregulation. Potential yield increases from removing rocks from cropland or pastoral regions will not compensate for the net loss of biodiversity or non-renewable habitat such as rocks. We propose that appropriate retention and management of rock habitat is required to conserve reptile diversity in agricultural landscapes, and that financial incentives to prevent the expansion and transformation of non-arable landscapes to cropland are required to prevent ongoing loss of biodiversity.

ACKNOWLEDGEMENTS

The authors respectfully acknowledge the traditional owners, their Elders past, present and future, and their Nations on which this publication is based. Images courtesy of Steve Wilson (*T. condaminensis*, *C. adelaidensis*), Damian Lettoof (*D. impar*), Jon-Paul Emery (*T. adelaidensis*), Jules Farquhar (*A. aurita*, *D. molleri*), Jordan Voss (*A. pinguis*, *D. grayii*), Jordan de Jong (*L. yuna*) and Henry Cook (*P. flagellum*). Simon MacDonald (CSU) assisted with ALA data extraction.

AUTHORS' CONTRIBUTIONS

D.R.M., H.M and D.G.N. conceived the ideas and designed the methodology; D.R.M. collated the data and led the writing of the manuscript; H.M. analysed the data. All the authors contributed critically to the drafts and gave final approval for publication.

DATA AVAILABILITY STATEMENT

Data available via the Dryad Digital Repository https://doi.org/10.5061/dryad.slrn8pk7h (Michael et al., 2021).

ORCID

Damian R. Michael https://orcid.org/0000-0003-3980-9723
Reid Tingley https://orcid.org/0000-0002-7630-7434
David G. Chapple https://orcid.org/0000-0002-7720-6280
Jackie O'Sullivan https://orcid.org/0000-0003-1766-0585
Dale G. Nimmo https://orcid.org/0000-0002-9814-1009

REFERENCES

Anderson, R. C., Fralish, J. S., & Baskin, J. M. (2007). *Savannas, barrens, and rock outcrop plant communities of North America*. Cambridge University Press.

Böhm, M., Collen, B., Baillie, J. E. M., Bowles, P., Chanson, J., Cox, N., Hammerson, G., Hoffmann, M., Livingstone, S. R., Ram, M., Rhodin, A. G. J., Stuart, S. N., van Dijk, P. P., Young, B. E., Afuang, L. E., Aghasyan, A., García, A., Aguilar, C., Ajtic, R., … Zug, G. (2013). The conservation status of the world's reptiles. *Biological Conservation*, *157*, 372–385. https://doi.org/10.1016/j.biocon.2012.07.015

Burke, A. (2003). Inselbergs in a changing world - global trends. *Diversity and Distributions*, *9*, 375–383. https://doi.org/10.1046/j.1472-4642.2003.00035.x

Chapple, D. G., Tingley, R., Mitchell, N. J., Macdonald, S. L., Keogh, J. S., Shea, G. M., Bowles, P., Cox, N. A., & Woinarski, J. C. Z. (2019). *The Action Plan for Australian Lizards and Snakes 2017*. CSIRO Publishing.

Collier, M. J. (2013). Field boundary stone walls as exemplars of 'novel' ecosystems. *Landscape Research*, *38*, 141–150. https://doi.org/10.1080/01426397.2012.682567

Daily, G. C., Ceballos, G., Pacheco, J., Suzán, G., & Sánchez-Azofeifa, G. A. (2003). Countryside biogeography of neotropical mammals: Conservation opportunities in agricultural landscapes of Costa Rica. *Conservation Biology*, *17*, 1814–1826. https://doi.org/10.1111/j.1523-1739.2003.00298.x

Daily, G. C., Ehrlich, P. R., & Sánchez-Azofeifa, G. A. (2001). Countryside biogeography: Use of human-dominated habitats by the avifauna of southern Costa Rica. *Ecological Applications*, *11*, 1–13.

de Graaff, M. A., Hornslein, N., Throop, H. L., Kardol, P., & van Diepen, L. T. (2019). Effects of agricultural intensification on soil biodiversity and implications for ecosystem functioning: A meta-analysis. *Advances in Agronomy*, *155*, 1–44.

Ellis, E. C., Klein Goldewijk, K., Siebert, S., Lightman, D., & Ramankutty, N. (2010). Anthropogenic transformation of the biomes, 1700 to 2000. *Global Ecology and Biogeography*, *19*, 589–606. https://doi.org/10.1111/j.1466-8238.2010.00540.x

Emmerson, M., Morales, M. B., Oñate, J. J., Batary, P., Berendse, F., Liira, J., Aavik, T., Guerrero, I., Bommarco, R., Eggers, S., & Pärt, T. (2016). How agricultural intensification affects biodiversity and ecosystem services. *Advances in Ecological Research*, *55*, 43–97.

Fitzsimons, J. A., & Michael, D. R. (2017). Rocky outcrops: A hard road in the conservation of critical habitats. *Biological Conservation*, *211*, 36–44. https://doi.org/10.1016/j.biocon.2016.11.019

Foley, J. A., DeFries, R., Asner, G. P., Barford, C., Bonan, G., Carpenter, S. R., Chapin, F. S., Coe, M. T., Daily, G. C., Gibbs, H. K., Helkowski, J. H., Holloway, T., Howard, E. A., Kucharik, C. J., Monfredo, C., Patz, J. A., Prentice, C., Ramankutty, N., & Synder, P. K. (2005). Global consequences of land use. *Science*, *309*, 570–574. https://doi.org/10.1126/science.1111772

Ford, H. A., Barrett, G. W., Saunders, D. A., & Recher, H. F. (2001). Why have birds in the woodlands of southern Australia declined? *Biological*

Conservation, *97*, 71–88. https://doi.org/10.1016/S0006-3207(00)00101-4
Frishkoff, L. O., Ke, A., Martins, I. S., Olimpi, E. M., & Karp, D. S. (2019). Countryside biogeography: The controls of species distributions in human-dominated landscapes. *Current Landscape Ecology Reports*, *4*, 15–30. https://doi.org/10.1007/s40823-019-00037-5
Ghosh, D., & Basu, P. (2020). Factors influencing herpetofauna abundance and diversity in a tropical agricultural landscape mosaic. *Biotropica*, *52*, 927–937. https://doi.org/10.1111/btp.12799
Gibbons, J. W., Scott, D. E., Ryan, T. J., Buhlmann, K. A., Tuberville, T. D., Metts, B. S., Greene, J. L., Mills, T., Leiden, Y., Poppy, S., & Winne, C. T. (2000). The global decline of Reptiles, Déjà Vu Amphibians. *BioScience*, *50*, 653–666.
Gibson, N., Yates, C. J., & Dillon, R. (2010). Plant communities of the ironstone ranges of South Western Australia: Hotspots for plant diversity and mineral deposits. *Biodiversity and Conservation*, *19*, 3951–3962. https://doi.org/10.1007/s10531-010-9939-1
Godfray, H. C. J., Beddington, J. R., Crute, I. R., Haddad, L., Lawrence, D., Muir, J. F., Pretty, J., Robinson, S., Thomas, S. M., & Toulmin, C. (2010). Food security: The challenge of feeding 9 billion people. *Science*, *327*, 812–818. https://doi.org/10.1126/science.1185383
Goldingay, R. L., & Newell, D. A. (2017). Small-scale field experiments provide important insights to restore the rock habitat of Australia's most endangered snake. *Restoration Ecology*, *25*, 243–252. https://doi.org/10.1111/rec.12421
Goldsbrough, C. L., Shine, R., & Hochuli, D. F. (2006). Factors affecting retreat-site selection by coppertail skinks (*Ctenotus taeniolatus*) from sandstone outcrops in eastern Australia. *Austral Ecology*, *31*, 326–336. https://doi.org/10.1111/j.1442-9993.2006.01561.x
Green, J. M., Croft, S. A., Durán, A. P., Balmford, A. P., Burgess, N. D., Fick, S., Gardner, T. A., Godar, J., Suavet, C., Virah-Sawmy, M., Young, L. E., & West, C. D. (2019). Linking global drivers of agricultural trade to on-the-ground impacts on biodiversity. *Proceedings of the National Academy of Sciences of the United States of America*, *116*, 23202–23208. https://doi.org/10.1073/pnas.1905618116
Harris, G., Thirgood, S., Hopcraft, J. G. C., Cromsigt, J. P., & Berger, J. (2009). Global decline in aggregated migrations of large terrestrial mammals. *Endangered Species Research*, *7*, 55–76. https://doi.org/10.3354/esr00173
Harris, R., Mioduszewski, P., & Molony, L. (2010). Vegetation responses to chaining in an isolated remnant in Western Australia's wheatbelt. *Journal of the Royal Society of Western Australia*, *93*, 1–11.
Haslem, A., & Bennett, A. F. (2008). Countryside elements and the conservation of birds in agricultural environments. *Agriculture, Ecosystems & Environment*, *125*, 191–203. https://doi.org/10.1016/j.agee.2008.01.001
Hobbs, R. J. (2003). The wheatbelt of Western Australia. *Pacific Conservation Biology*, *9*, 9–11. https://doi.org/10.1071/PC030009
Hobbs, R. J., & Saunders, D. (1991). Re-integrating fragmented landscapes—A preliminary framework for the Western Australian wheatbelt. *Journal of Environmental Management*, *33*, 161–167. https://doi.org/10.1016/S0301-4797(05)80092-1
Hurtt, G. C., Frolking, S., Fearon, M., Moore, B., Shevliakova, E., Malyshev, S., Pacala, S. W., & Houghton, R. A. (2006). The underpinnings of land-use history: Three centuries of global gridded land-use transitions, wood-harvest activity, and resulting secondary lands. *Global Change Biology*, *12*, 1208–1229. https://doi.org/10.1111/j.1365-2486.2006.01150.x
IUCN. (2020). *The IUCN Red List of Threatened Species*. Version 2020-2. https://www.iucn.redlist.org. Downloaded on 09 July 2020
Landis, D. A. (2017). Designing agricultural landscapes for biodiversity-based ecosystem services. *Basic and Applied Ecology*, *18*, 1–12. https://doi.org/10.1016/j.baae.2016.07.005
Macfadyen, S., Cunningham, S. A., Costamagna, A. C., & Schellhorn, N. A. (2012). Managing ecosystem services and biodiversity conservation in agricultural landscapes: Are the solutions the same? *Journal of Applied Ecology*, *49*, 690–694. https://doi.org/10.1111/j.1365-2664.2012.02132.x
Melville, J., Chaplin, K., Hutchinson, M., Sumner, J., Gruber, B., MacDonald, A. J., & Sarre, S. D. (2019). Taxonomy and conservation of grassland earless dragons: New species and an assessment of the first possible extinction of a reptile on mainland Australia. *Royal Society Open Science*, *6*, 190233. https://doi.org/10.1098/rsos.190233
Mendenhall, C. D., Sekercioglu, C. H., Brenes, F. O., Ehrlich, P. R., & Daily, G. C. (2011). Predictive model for sustaining biodiversity in tropical countryside. *Proceedings of the National Academy of Sciences of the United States of America*, *108*, 16313–16316. https://doi.org/10.1073/pnas.1111687108
Michael, D. R. (2020). Removal of critical rock habitat threatens biodiversity. ESA Hot Topics, 20 August. Available at: https://www.ecolsoc.org.au/?hottopic-entry=removal-of-critical-rock-habitat-threatens-biodiversity
Michael, D. R., Cunningham, R. B., & Lindenmayer, D. B. (2008). A forgotten habitat? Granite inselbergs conserve reptile diversity in fragmented agricultural landscapes. *Journal of Applied Ecology*, *45*, 1742–1752. https://doi.org/10.1111/j.1365-2664.2008.01567.x
Michael, D. R., Kay, G. M., Crane, M., Florance, D., MacGregor, C., Okada, S., McBurney, L., Blair, D., & Lindenmayer, D. B. (2015). Ecological niche breadth and microhabitat guild structure in temperate Australian reptiles: Implications for natural resource management in endangered grassy woodland ecosystems. *Austral Ecology*, *40*, 651–660. https://doi.org/10.1111/aec.12232
Michael, D. R., & Lindenmayer, D. B. (2018a). *Rocky outcrops in Australia: Ecology, conservation and management*. CSIRO Publishing, Collingwood, Melbourne.
Michael, D. R., & Lindenmayer, D. B. (2018b). *A new wave of rock removal could spell disaster for farmland wildlife*. The Conversation, 10 April. Retrieved from https://theconversation.com/a-new-wave-of-rock-removal-could-spell-disaster-for-farmland-wildlife-94305
Michael, D. R., Lindenmayer, D. B., & Cunningham, R. B. (2010). Managing rock outcrops to improve biodiversity conservation in Australian agricultural landscapes. *Ecological Management & Restoration*, *11*, 43–50. https://doi.org/10.1111/j.1442-8903.2010.00512.x
Michael, D. R., Moore, H., Wassens, S., Craig, M. D., Tingley, R., Chapple, D. G., O'Sullivan, J., Hobbs, R. J., & Nimmo, D. G. (2021). Data from: Rock removal associated with agricultural intensification will exacerbate loss of reptile diversity. *Dryad Digital Repository*, https://doi.org/10.5061/dryad.slrn8pk7h
Murray-Wooley, C., & Raitz, K. (2015). *Rock fences of the bluegrass*. University Press of Kentucky.
Nopper, J., Lauströer, B., Rödel, M. O., & Ganzhorn, J. U. (2017). A structurally enriched agricultural landscape maintains high reptile diversity in sub-arid south-western Madagascar. *Journal of Applied Ecology*, *54*, 480–488. https://doi.org/10.1111/1365-2664.12752
Pike, D., Croak, B., Webb, J., & Shine, R. (2010). Subtle–but easily reversible–anthropogenic disturbance seriously degrades habitat quality for rock-dwelling reptiles. *Animal Conservation*, *13*, 411–418. https://doi.org/10.1111/j.1469-1795.2010.00356.x
Pinder, A., Halse, S., Shiel, R., & McRae, J. (2000). Granite outcrop pools in south-western Australia: Foci of diversification and refugia for aquatic invertebrates. *Journal of the Royal Society of Western Australia*, *83*, 149–161.
Pulsford, S. A., Barton, P. S., Driscoll, D. A., Kay, G. M., & Lindenmayer, D. B. (2018). Reptiles and frogs use most land cover types as habitat in a fine-grained agricultural landscape. *Austral Ecology*, *43*, 502–513. https://doi.org/10.1111/aec.12587
Ray, D. K., Ramankutty, N., Mueller, N. D., West, P. C., & Foley, J. A. (2012). Recent patterns of crop yield growth and stagnation. *Nature Communications*, *3*, 1–7. https://doi.org/10.1038/ncomms2296

Sala, O. E., Chapin, F. S., Armesto, J. J., Berlow, E., Bloomfield, J., Dirzo, R., Huber-Sanwald, E., Huenneke, L. F., Jackson, R. B., Kinzig, A., Leemansm, R., Lodge, D. M., Mooney, H. A., Oesterheld, M., Poff, N. L., Sykes, M. T., Walker, B. H., Walker, M., & Wall, D. H. (2000). Global biodiversity scenarios for the year 2100. *Science*, *287*, 1770–1774.

Saunders, D. (1989). Changes in the avifauna of a region, district and remnant as a result of fragmentation of native vegetation: The wheatbelt of Western Australia. A case study. *Biological Conservation*, *50*, 99–135. https://doi.org/10.1016/0006-3207(89)90007-4

Şekercioğlu, Ç. H., Daily, G. C., & Ehrlich, P. R. (2004). Ecosystem consequences of bird declines. *Proceedings of the National Academy of Sciences of the United States of America*, *101*, 18042–18047. https://doi.org/10.1073/pnas.0408049101

Shine, R., Webb, J. K., Fitzgerald, M., & Sumner, J. (1998). The impact of bush-rock removal on an endangered snake species, *Hoplocephalus bungaroides* (Serpentes: Elapidae). *Wildlife Research*, *25*, 285–295. https://doi.org/10.1071/WR97022

Speziale, K. L., & Ezcurra, C. (2015). Rock outcrops as potential biodiversity refugia under climate change in North Patagonia. *Plant Ecology & Diversity*, *8*, 353–361. https://doi.org/10.1080/17550874.2014.983200

Thomas, J. A., Telfer, M., Roy, D. B., Preston, C. D., Greenwood, J., Asher, J., Fox, R., Clarke, R. T., & Lawton, J. H. (2004). Comparative losses of British butterflies, birds, and plants and the global extinction crisis. *Science*, *303*, 1879–1881. https://doi.org/10.1126/science.1095046

Tingley, R., Macdonald, S. L., Mitchell, N. J., Woinarski, J. C. Z., Meiri, S., Bowles, P., Cox, N. A., Shea, G. M., Böhm, M., Chanson, J., Tognelli, M. F., Harris, J., Walke, C., Harrison, N., Victor, S., Woods, C., Amey, A. P., Bamford, M., Catt, G., … Chapple, D. G. (2019). Geographic and taxonomic patterns of extinction risk in Australian squamates. *Biological Conservation*, *238*, 108203. https://doi.org/10.1016/j.biocon.2019.108203

Todd, B. D., Wilson, J. D., & Gibbons, J. W. (2010). The global status of reptiles and causes of their decline. In D. W. Sparling, G. Linder, C. A. Bishop, & S. Krest (Eds.), *Ecotoxicology of amphibians and reptiles* (2nd ed., pp. 48–61). CRC Press.

Wang, S., & Loreau, M. (2016). Biodiversity and ecosystem stability across scales in metacommunities. *Ecology Letters*, *19*, 510–518. https://doi.org/10.1111/ele.12582

Yates, C. J., & Hobbs, R. J. (2000). Temperate eucalypt woodlands in Australia-an overview. In R. J. Hobbs & C. J. Yates (Eds.), *Temperate eucalypt woodlands in Australia: Biology, conservation, management and restoration* (pp. 1–5). Surrey Beatty and Sons.

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

How to -cite this article: Michael DR, Moore H, Wassens S, et al. Rock removal associated with agricultural intensification will exacerbate the loss of reptile diversity. *J Appl Ecol*. 2021;58:1557–1565. https://doi.org/10.1111/1365-2664.13897