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Taxonomic revision reveals potential impacts of Black Summer megafires on a cryptic species

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ABSTRACT

Context. Sound taxonomy is the cornerstone of biodiversity conservation. Without a fundamental understanding of species delimitations, as well as their distributions and ecological requirements, our ability to conserve them is drastically impeded. Cryptic species – two or more distinct species currently classified as a single species – present a significant challenge to biodiversity conservation. How do we assess the conservation status and address potential drivers of extinction if we are unaware of a species' existence? Here, we present a case where the reclassification of a species formerly considered widespread and secure – the sugar glider (*Petaurus breviceps*) – has dramatically increased our understanding of the potential impacts of the catastrophic 2019–20 Australian megafires to this species. **Methods.** We modelled and mapped the distribution of the former and reclassified sugar glider (*Petaurus breviceps*). We then compared the proportional overlap of fire severity classes between the former and reclassified distribution, and intersected habitat suitability and fire severity to help identify areas of important habitat following the 2019–20 fires. **Key results.** Taxonomic revision means that the distribution of this iconic species appears to have been reduced to 8% of its formerly accepted range. Whereas the 2019–20 Australian megafires overlapped with 8% of the formerly accepted range, they overlapped with 33% of the proposed range of the redefined *Petaurus breviceps*. **Conclusions.** Our study serves as a sombre example of the substantial risk of underestimating impacts of mega-disturbance on cryptic species, and hence the urgent need for cataloguing Earth's biodiversity in the age of megafire.

Keywords: dark extinction, mammal, marsupial, mega-fire, Petauridae, *Petaurus breviceps*, species distribution model, threat assessment.

Introduction

Sound taxonomy is vital to biodiversity conservation (Garnett and Christidis 2017). It allows clear delineation of species' distributions and population size, which facilitates assessments of extinction risk and reveals the need for conservation interventions (Mace 2004). Regrettably, there are many examples of species' decline and extinction being realised only after taxonomic review (Régnier *et al.* 2015) – sometimes termed 'dark extinctions' (Boehm and Cronk 2021). For example, a recent taxonomic revision resulted in elevation to species status of the Christmas Island shrew (*Crocidura trichura*) a decade or so after the species' likely extinction (Eldridge *et al.* 2014). The cryptic treehunter (*Cichlocolaptes mazarbarnetti*) of northeast Brazil was formally described in 2014 (Barnett and Buzzetti 2014), but has not been sighted since 2007 and is presumed extinct (Lees and Pimm 2015). Cryptic species – two or more similar but distinct species classified as a single species (Bickford *et al.* 2007) – present a particular challenge to conservation, especially when a species regarded as widespread and secure contains multiple distinct species with far narrower distributions (Beheregaray *et al.* 2017). As the scale and intensity of disturbance across the globe grows, so too does the risk of losing species to extinction before they are described (Boehm and Cronk 2021).

The 2019–20 Australian megafires commanded global attention. From August 2019 to March 2020, more than 10 million hectares of south-eastern Australia burned in wildfires, much of it at high severity (Nolan *et al.* 2020; Wintle *et al.* 2020). These fires affected habitat for 832 native vertebrates, with 70 of these taxa having >30% of their known habitat burned (Ward *et al.* 2020). While the megafires burned, scientists were in the final stages of re-defining the taxonomy of a charismatic species – the sugar glider (family Petauridae) – previously considered widespread and secure. Using a combination of morphological and genetic data, this taxonomic revision identified these small, arboreal, gliding marsupials to be three distinct but cryptic species (Cremona *et al.* 2021). This revision saw the previously described northern sugar glider subspecies, *Petaurus breviceps ariel* elevated to full species [savanna glider *Petaurus ariel* (Gould, 1842)], the resurrection of a previously synonymised species which occurs across vast areas of eastern Australia, from South Australia to north Queensland (Krefft's glider *Petaurus notatus* Peters, 1859), and restriction of the nominate species to coastal areas of New South Wales and southern Queensland [sugar glider *P. breviceps* (Waterhouse, 1838)] (Cremona *et al.* 2021). While fires within the Australian government's preliminary analysis area (i.e. the area within which the bushfire season appeared particularly anomalous) affected both *P. notatus* and the reclassified *P. breviceps*, the latter's distribution appears particularly coincident with the fire-affected areas (Fig. 1).

Small gliders are known to be vulnerable to high severity fires, likely due to a combination of direct mortality and loss of key resources (Lindenmayer *et al.* 2013), especially hollow-bearing trees (Gibbons and Lindenmayer 2002). Given this, and the much narrower proposed distribution of *P. breviceps* following taxonomic revision, there is an urgent need to re-assess the potential impacts of the 2019–20 Australian megafires on this species. Here, we model and map the

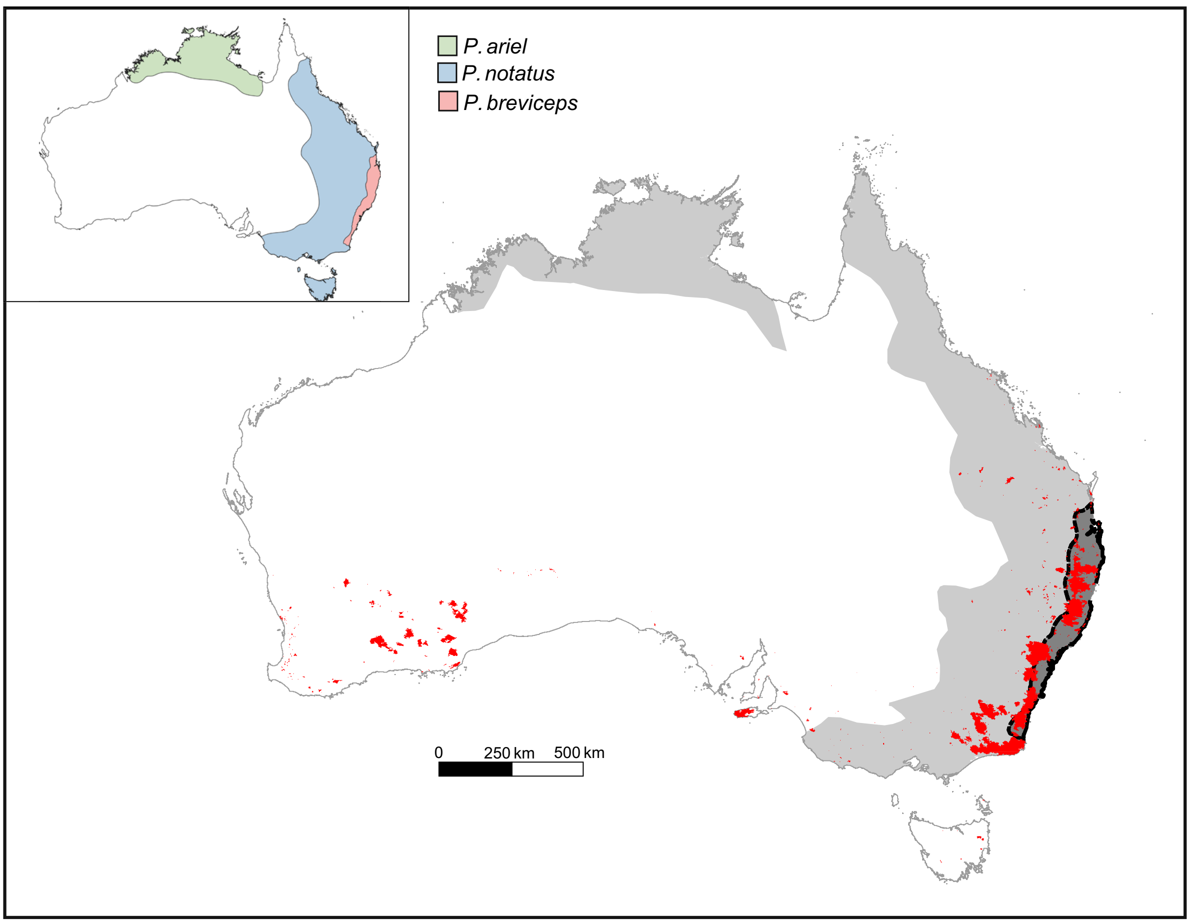

Fig. 1. The area burnt by the 2019–20 Australian megafires (red) informed by the Google Earth Engine Burnt Area Map (Department of Industry Planning & Environment (DIPE) 2020) overlayed on the former (light grey) and reclassified (dark grey) geographic range of the sugar glider *Petaurus breviceps* (Waterhouse, 1838) as described by Cremona *et al.* (2021). Because sugar gliders were introduced to Tasmania, we excluded all Tasmanian records. Inset: Distributions of the newly resolved species in the sugar glider complex as assigned by Cremona *et al.* (2021): savanna glider (*Petaurus ariel*) (green); Krefft's glider (*Petaurus notatus*) (blue); and sugar glider (*Petaurus breviceps*).

distribution of the former and reclassified *P. breviceps* and calculate the proportion of its habitat that burned during the 2019–20 bushfire season. We compare the proportional overlap of fire severity classes between the former and reclassified *P. breviceps* distribution and intersect habitat suitability and fire severity to help identify areas of important habitat following the 2019–20 fires. Our study highlights the vital importance of sound taxonomy for measuring the threats posed to species, including those from mega-disturbance.

Methods

Ethical approval

All data used and generated in this study came from publicly accessible repositories (Atlas of Living Australia and Google Earth Engine Burnt Area Mapping) and approval by an animal ethics committee was unnecessary.

Occurrence data

Occurrence records of *P. breviceps* were collected from the Atlas of Living Australia (https://www.ala.org.au) and were subject to a filtering process. Because sugar gliders were introduced to Tasmania (Campbell *et al.* 2018), we excluded all Tasmanian records. We then removed dubious records by clipping all records to either the former *P. breviceps* range (based on IUCN maps; IUCN 2021) or the proposed reclassified *P. breviceps* range (Cremona *et al.* 2021) to create two sets of occurrence data (i.e. one each for the former and reclassified *P. breviceps*). It is worth noting, however, that the reclassified distribution of *P. breviceps* proposed by Cremona *et al.* (2021) is an estimate based on genetic and morphological data. Although evidence currently suggests that the Great Dividing Range acts as the western edge of the distribution of *P. breviceps* (Cremona *et al.* 2021), we cannot be certain of this. However, for the purposes of this study we have assumed it to be so. In both datasets, records were removed if: (1) they were missing date information or were collected before the year 2000; or (2) they had high locational uncertainty (e.g. vague or inaccurate locations). Records within any 1 × 1 km grid cell were collapsed into a single record. The final filtered data base consisted of 7777 presence records within the formerly considered geographic range, and 5089 within the reclassified range (see Fig. S1).

Geographic range estimation

We mapped the extent of occurrence (EOO) of the former and reclassified *P. breviceps* using the occurrence datasets. EOO is defined as the area enclosed by the shortest possible boundary containing all sites in which a species is known to be present (IUCN 2021). We calculated EOO as α-hulls (a generalisation of convex polygons that allow for breaks in species ranges), using the '*alphahull*' package in R ver. 3.6.2 (R Core Team 2021), specifying an α value of two (IUCN 2021). We regarded EOO as preferable to area of occupancy because maps of the latter showed clear spatial bias indicated by high densities of records surrounding major capital cities.

Species distribution modelling

Using the Maxent algorithm, we developed species distribution models (SDMs) based on the two occurrence datasets outlined above (Phillips *et al.* 2006). We selected SDM environmental layers based on their likely importance to *P. breviceps* habitat suitability. All environmental layers were resampled to 1 × 1 km resolution prior to being included in models. A set of 10 000 background points were included within the SDM to compare densities in environmental values occupied by *P. breviceps* with those of the surrounding unoccupied environment. We addressed sample bias within the study area with a 'target group' background sampling approach (Phillips *et al.* 2009) (see Fig. S1). We defined the target group as arboreal mammal species occurring within the study area, including *P. breviceps*. Sampling intensity for target group species was mapped by converting species presence records of the target group to a kernel density map using the *kde2d* function of the '*MASS*' package (Venables and Ripley 2002) set with the default kernel bandwidth. Model performance was measured as area under the curve of the receiver operating characteristic plot, and the contribution of environmental variables to the response variable was measured as permutation importance (Phillips 2005).

Fire overlap

We overlapped the former and reclassified *P. breviceps* EOO with 2019–20 bushfire severity maps from the Google Earth Engine Burnt Area Mapping (GEEBAM; Department of Industry Planning & Environment (DIPE) 2020). GEEBAM classifies the cells within the fire boundary as one of five fire severity classes: no data (cleared land, water etc.); unburnt (unburnt and lightly burnt); low and moderately burnt (some or moderate change post-fire); high severity (vegetation mostly scorched); and very high severity (vegetation clearly consumed). When calculating fire overlap, we considered only fires occurring within the 'preliminary area for environmental analysis' (following Legge *et al.* 2020). This area encompasses bioregions that were deemed to have experienced anomalously substantial fire activity during the 2019–20 bushfire season. Overlap measures were calculated using QGIS ver. 3.14.1 (QGIS Development Team 2021).

We created a fire severity × habitat quality matrix to help identify the spatial intersection between fire severity and habitat quality for the reclassified *P. breviceps*. First, we classified the continuous output of relative habitat quality derived from the SDM into four discrete classes: low quality (relative likelihood of occurrence 0–0.25); low–medium quality (relative likelihood of occurrence 0.25–0.50); medium–high quality (relative likelihood of occurrence 0.5–0.75); and high quality (relative likelihood of occurrence 0.75–1). We then combined the reclassified SDM with the GEEBAM fire severity layer to derive a layer with 16 unique combinations of all combinations of habitat quality and fire severity and mapped this across the range of *P. breviceps*.

Results

Based on the proposed distribution for the reclassified *P. breviceps* Cremona *et al.* (2021), the range of the former *P. breviceps* is 12 times larger than the reclassified species range based on EOO (1 276 383 km^2 cf. 105 723 km^2; Figs 1 and 2). The 2019–20 fire overlapped with 8.1% of the former *P. breviceps* EOO (103 931 km^2) compared to 32.7% of the reclassified *P. breviceps* EOO (34 529 km^2; Figs 1–3). Fire severity maps showed that 13.3% of the reclassified *P. breviceps* EOO burned at either high (9.6%) or very high (3.7%) severity, compared to only 3.3% of the former EOO falling within those two categories (high = 2.3%; very high = 1%; Fig. 3). Intersecting habitat quality and fire severity showed areas of high-quality habitat were affected by high severity fires, particularly areas in the NSW south coast (Dampier and Bodalla State Forests; Fig. 4*c*). High quality unburned refuges within the fire boundary occur on the mid-north coast of NSW, in areas such as Washpool and Cottan-Bimbang National Parks (Fig. 4*a*).

Discussion

This study highlights the significant contribution that taxonomic revision can make to conservation. In this case, the taxonomic revision affected a common and long-recognised species in an ostensibly well-known group of animals (i.e. mammals). This revision resulted in a large reduction in the geographic distribution of one of the three reclassified constituent species, and a substantial increase in the proportion of its habitat impacted by Australia's 2019–20 megafires. Based on available evidence for the species' extent, approximately a third of the distribution of the reclassified *P. breviceps* was impacted by fire, with ~13% severely burned, including high-quality habitat. There is no doubt that the insufficient taxonomic resolution that plagues most other animal classes has led to equally dramatic, yet undetected, impacts on currently undescribed species (Saunders *et al.* 2021). Thus, the full impacts of the 2019–20 megafires on Australia's biodiversity are unlikely to be apparent until more species are identified and described, and species complexes resolved (Catullo *et al.* 2021).

This study underscores the ongoing and considerable potential for substantial impacts to and extinctions of undescribed species ('dark extinctions'; Boehm and Cronk 2021)

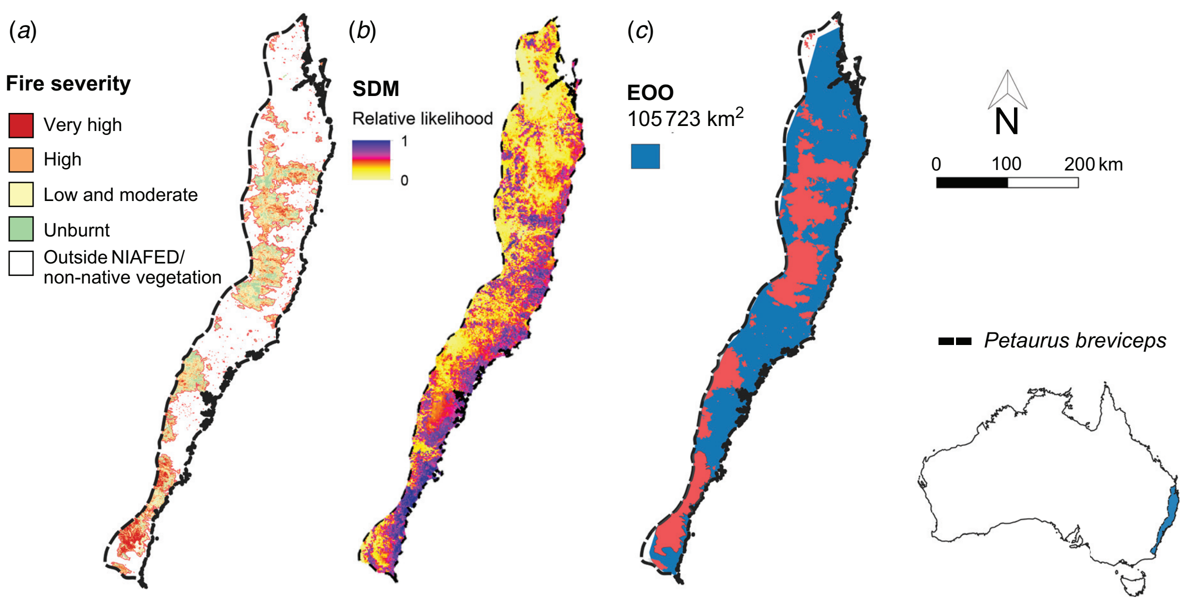

Fig. 2. Spatial distribution of (*a*) the 2019–20 megafires classified into fire severity classes, and two measures of the geographic range of the reclassified sugar glider *Petaurus breviceps* (NIAFED, National Indicative Aggregated Fire Extent Dataset); (*b*) suitable habitat derived from a Maxent model; and (*c*) extent of occurrence (EOO). In pane (*c*), range estimate is blue and the 2019–20 fire boundaries are red. The dashed line represents the species' range as described in Cremona *et al.* (2021).

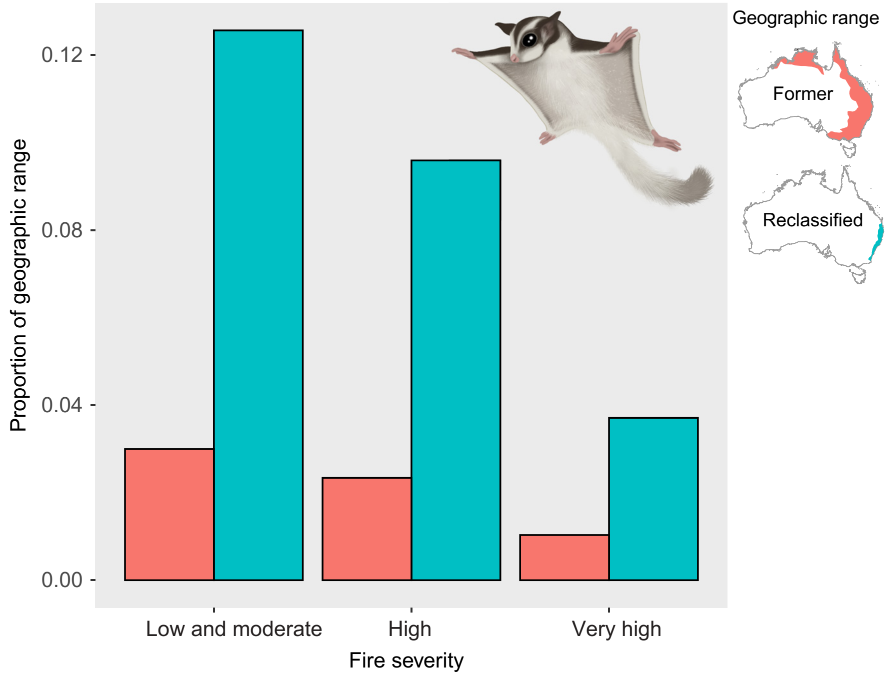

Fig. 3. Proportion of the former (light red) and reclassified (light blue) geographic range of the sugar glider *Petaurus breviceps* (Waterhouse, 1838) as described by Cremona *et al.* (2021) that burnt in the 2019–20 Australian megafires as informed by the Google Earth Engine Burnt Area Map (Department of Industry Planning & Environment (DIPE) 2020).

in an age of increasingly large-scale disturbances. The 2019–20 Australian megafires burned ~10.4 million hectares, an area nearly the size of England (Wintle *et al.* 2020). These fires were not only unprecedented in their scale, but also in their severity – some 1.8 million hectares of land burnt at high severity. Recent megafires in California and the Amazon (Escobar 2019; Barlow *et al.* 2020) were also unprecedented in scale (although smaller than the Australian fires) and captured the world's attention. The footprint of mega-disturbances across broad areas encompassed an unknown number of undescribed species that may well become examples of dark extinctions. Boehm and Cronk (2021) suggest one way of avoiding 'dark extinctions' is to prioritise taxonomic efforts in areas of high endemism, especially areas of high endemism that are subject to disturbance. Eastern Australia is recognised as an ecoregion of high vertebrate endemism (Lamoreux *et al.* 2006). Appropriately recognising threats and avoiding unknown extinctions of undescribed species in the age of megafire will require a significant investment in taxonomy, a field that is under-appreciated and under-resourced (Wheeler 2004). While species are typically thought of as the base units of biodiversity, where taxonomic resolution is potentially unresolved, an alternative approach may be to use genetic data to conserve lineage diversity (Rosauer *et al.* 2016; Coates *et al.* 2018), rather than relying solely on conserving described species diversity.

Unfortunately, there is currently very little known about the effects of high severity wildfire on populations of sugar gliders through their reclassified range and, although less than ideal, we are mostly reliant on information on the effects of high severity fire on a closely related species (i.e. Krefft's glider) in a different ecosystem (i.e. mountane ash forest). A previous study of responses to high severity fire found that Krefft's gliders (*P. notatus*; formerly subsumed in *P. breviceps*) were observed 3 years post-fire at just 3% of sites burned in the 2009 Black Saturday bushfires compared to 17% of sites in unburned mountain ash forests (Lindenmayer *et al.* 2013). Encouragingly, sugar glider site occupancy in unburnt coastal eucalypt forests appears to be considerably higher than that of Kreftt's gliders in mountain ash forests. Occupancies of sugar gliders at 40–100% of survey sites have been observed through their reclassified range (Kavanagh *et al.* 1995; Wintle *et al.* 2005; Goldingay *et al.* 2015; Goldingay 2021), potentially increasing the likelihood and pace of recovery and recolonisation of severely fire-affected sites. Although a study of sugar gliders in their reclassified range found no influence of fire on *P. breviceps* 5-year post-fire (Kavanagh *et al.* 1995), fire severity was not characterised in this study, and it is unclear whether the same response would be observed following fires of high severity.

In some Australian forests, arboreal mammals are highly vulnerable to the effects of severe fire, particularly obligate hollow-users (Lindenmayer *et al.* 2021). While fire can play

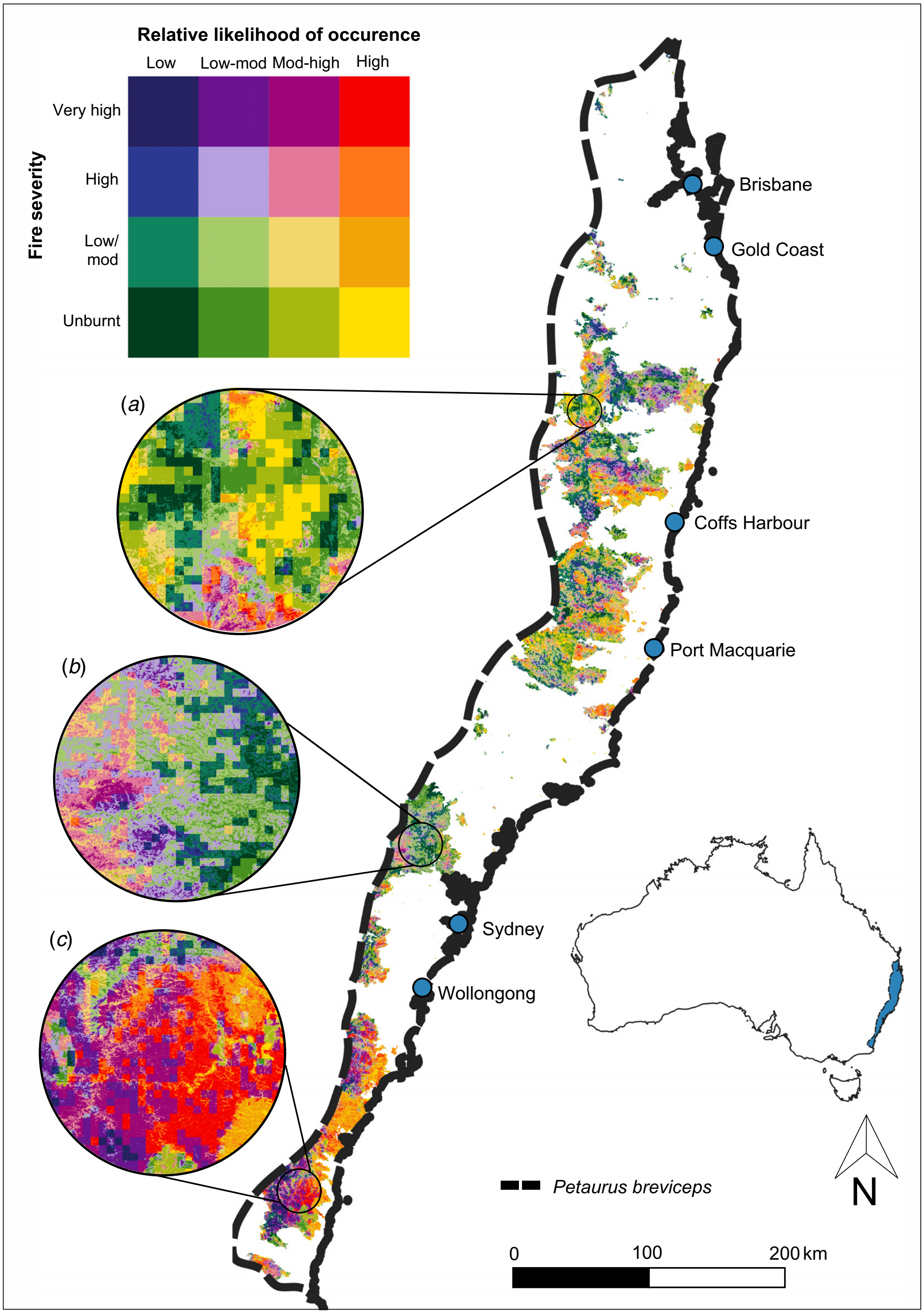

Fig. 4. Comparison between relative likelihood of occurrence of the reclassified sugar glider *Petaurus breviceps* based on a species distribution model and fire severity mapping of the 2019–20 Australian megafires as informed by the Google Earth Engine Burnt Area Map (Department of Industry Planning & Environment (DIPE) 2020). (*a*) Washpool National Park was unburnt or experienced predominantly low severity fires in high-quality sugar glider habitat; (*b*) Yengo and Wollemi National Parks experienced predominantly low to moderate fires in low-quality habitat; and (*c*) Dampier and Bodalla State Forests experienced predominantly high and very high severity fires in high-quality habitat.

an important role in accelerating the formation of tree hollows (Adkins 2006), it can also have a significant effect on the death, collapse and consequent loss of large hollow-bearing trees. Following the 2009 Black Saturday fires in montane ash forests of Victoria, 79% of large hollow-bearing trees died and 57–100% of dead trees or stags were consumed by the fires (Lindenmayer *et al.* 2012). Given that hollow formation in some eucalypts can take over a century (Gibbons and Lindenmayer 2002), the removal of such trees from the landscape can have long-lasting impacts on arboreal fauna. However, the impacts of fire on hollow-bearing trees in the eucalypt forests of south-eastern Australia are somewhat context- and species-dependent. Whilst fire has consistently been found to reduce dead hollow-bearing tree abundance (Eyre 2005; Eyre *et al.* 2010), more frequent fires (McLean *et al.* 2015) and fires of higher severity (Salmona *et al.* 2018) can result in more hollows, more frequent fires can result in fewer hollows (Salmona *et al.* 2018), and less time since fire can result in fewer hollow-bearing trees (Eyre *et al.* 2010; Haslem *et al.* 2012). Encouragingly, at least in some fire-affected regions, sugar gliders may not be as strongly dependent on hollow abundance as other sympatric gliders, such as threatened yellow-bellied gliders (Goldingay 2021). Fire may also affect some food resources for sugar gliders, which feed on plant exudates (e.g. honeydew and nectar) and a range of invertebrates (Smith 1982). Insect abundance also likely declined following the 2019–20 fires, at least temporarily (Swengel 2001; Legge *et al.* 2021). In the context of the 2019–20 bushfires, areas burned at high and very high severity may result in reduced abundance and occupancy of sugar gliders. Over what timespan these potential impacts are felt remains unclear and likely depends on the pace of post-fire vegetation succession, recovery rates and the temporal patterning of future fires. Clearly, studies investigating the impacts of high severity fire (and regimes including such fires) on populations of sugar gliders through their reclassified range are needed to assess the realised impact of such fires on this species.

In addition to highlighting the potential impacts of the 2019–20 bushfires on sugar gliders, while it will require validating in the field, we have outlined an approach to mapping the intersection of habitat quality and fire severity. Early analyses of the potential 2019–20 post-fire impacts on species measured the overlap between a species range and the fire boundary (Ward *et al.* 2020), but acknowledged that a more nuanced approach would improve assessment of impacts across a species' range. Here, we outlined one approach for defining a habitat quality × fire severity matrix, which facilitates a rapid assessment of the proportion of areas that differ in their habitat suitability that were burned at varying severities. Mapping this matrix helps to identify key areas of interest to conservation practitioners: key areas could be prioritised for protection (unburned refuges) or urgent interventions (severely burned, high-quality habitats), as well as helping to identify areas that are relatively low priorities, such as low-quality habitats burned at low severity. Such an approach could be used for other species within fire-affected areas. While this approach has broad utility for mapping priority areas for species across large areas, due to constraints in data resolution, it also has the potential to overlook environmental features which are important at the microhabitat scale. In acknowledging the potential importance of these features to species conservation, we suggest the current approach could be optimised with the inclusion of microhabitat data, such that species habitat quality can be assessed in more detail.

Our assessment of the revised taxonomic and geographic boundaries of *P. breviceps* suggest a potential for large-scale and long-term impacts of the 2019–20 megafire on this recently reclassified species. However, it is worth noting that very little work assessing the impacts of severe wildfires on sugar gliders has been conducted within their reclassified distribution. As a result, we have noted how severe wildfires have impacted a closely related species (*P. notatus*) in a different system (i.e. mountain ash; Lindenmayer *et al.* 2013). Future studies investigating the impacts of severe wildfire on sugar gliders are sorely needed if we are to better understand the threat they pose to this newly reclassified species. The 2019–20 fires provide an opportunity to fill this critical knowledge gap.

In addition, where taxonomy lags behind our understanding of the genetic structure of populations, we suggest future studies could benefit from assessing the impact of major disturbances on genetic lineages (see Rosauer *et al.* 2016; Coates *et al.* 2018; Catullo *et al.* 2021), striving to conserve population and lineage diversity, rather than solely focusing on the impacts to described species.

By comparing the range of the reclassified species with fire severity maps, we have demonstrated that this species was potentially considerably more impacted by the megafires than previous taxonomy indicated. This trend is likely true for other groups suffering from poor taxanomic resolution. Our study provides an instructive example of the substantial risk of under-estimating impacts of mega-disturbance on undescribed or poorly resolved species, and hence the urgent need for cataloguing Earth's biodiversity in the age of megafire.

Supplementary material

Supplementary material is available online.

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