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RESEARCH ARTICLE

Rapid on-ground assessment after the 2019–2020 megafires reveals new information on rare and threatened plants in northern New South Wales, Australia

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Abstract
Lack of ecological knowledge is a major challenge for effective conservation of threatened plant species in Australia as disturbance events, such as wildfire, increase in frequency and magnitude. Rapid on-ground surveys are increasingly important to inform recovery strategies for rare and threatened plants in response to extreme wildfire events, yet resources are rarely available to deploy time-sensitive surveys. Here, we utilize a rapid on-ground survey and monitoring program to document basic biological and ecological information for 21 rare and threatened plant species from the New England bioregion in northern New South Wales, which were affected by the catastrophic 2019–2020 megafires. Our results fill an important knowledge gap of ecology, population size, distribution and response to fire for these taxa, document for the first time a species distribution pattern within the Torrington State Conservation Area and reveal previously undocumented plant–insect interactions for nine species, including likely pollination of *Persoonia terminalis* ssp. *terminalis* and *Monotaxis macrophylla* by native bee (Hymenoptera) and fly (Diptera) species. Our findings reveal that two species (*Cassinia heleniae* and *Hakea macrorrhyncha*) have scarce distribution and low population sizes, despite neither having a conservation listing and their threat status should be urgently assessed. Simple rapid on-ground surveys can be more cost effective for delivering long-term conservation outcomes for rare and threatened taxa and we advocate that future funding and prioritisation processes must support the immediate delivery of such surveys in response to disturbance events.

KEYWORDS
Bolivia Hill, bushfire recovery, conservation, endangered, fire ecology, threatened species monitoring, Torrington, wildfire

INTRODUCTION

Catastrophic wildfire events, such as the 2019–2020 megafires that affected most of eastern Australia, are predicted to become more frequent and severe due to climate change (Dowdy et al., 2019). Wildfire is a common disturbance in Australian ecosystems, yet the responses and recovery potential of Australian vegetation after frequent intense wildfires is still poorly understood (Gallagher et al., 2021; Godfree et al., 2021). Estimates of recovery potential are often based on trait-based assumptions from closely related species or historical data, but are not always accurate across the range of a species (Vivian et al., 2010). The extent of the 2019–2020 megafires was unprecedented in contemporary Australian fire history and affected numerous ecosystems of fire-sensitive vegetation that may not fully recover (Collins et al., 2021; Gallagher et al., 2021). Studies that quantified the effects of the catastrophic wildfire event on vegetation and plant taxa, including threatened species, used large-scale spatial mapping of known distributions correlated with burned areas (Auld et al., 2020; Gallagher et al., 2021; Godfree et al., 2021). This approach is important as a priority method to guide policy responses, but can be more effective for conservation strategies when combined with on-ground surveys to determine post-wildfire local conditions, distributions and species interactions for populations of target plant species.

Rapid post-fire surveys to ascertain survival and demographic metrics of rare plant species become increasingly important when delivering recovery strategies in response to extreme disturbance events. Lack of biological knowledge, particularly understanding of distribution, life history, ecology and habitat requirements, is a major challenge for threatened plant conservation in Australia (Broadhurst & Coates, 2017). This deficiency of basic knowledge hampers our ability to focus attention on the best avenues for monitoring and recovery. In addition, it can mean that more well-studied species, for which immediate threats are known and for which recovery plans are published, are more likely to be prioritized for monitoring over less well-studied species (Lavery et al., 2021). Rare and restricted species are often overlooked in conservation prioritisation, because they are assumed to face fewer immediate threats compared to more widespread threatened species (Silcock, 2017). Overall, there is little guidance on how to design and implement surveys for rare plant populations to gain the basic knowledge needed to address key knowledge gaps, such as range, population size and habitat parameters (Keith, 2000; Wiser et al., 1998).

Rare species often occur in patchy microsites with eruptive population behaviour, clumped distributions and separated by large distances (Edwards et al., 2005; Gaston & Lawton, 1990). Strict random stratified designs are commonly proposed for surveys of rare plants in many Australian guidelines, as they are thought to provide the least biased estimates of occupancy (e.g., Cropper, 1993; Department of Environment, 1998). However, this strategy has low resolution power and is inefficient for capturing rare species with clumped distribution (Edwards et al., 2005; Lavery et al., 2021; Philippi, 2005). For rare species, it can be more effective to target searches to locations where they are more likely to be found, based on known or assumed habitat requirements of the species (Kalton & Anderson, 1986; Philippi, 2005), combined with random searching in other nearby habitats (Edwards et al., 2005; Poon & Margules, 2004).

Our project focuses on 21 rare and threatened plant species endemic to an area of northeastern New South Wales which was severely impacted by the 2019–2020 megafires. These plant species were included on a priority list of species identified as in urgent need of assessment and management intervention after the megafires by Department of Climate Change, Energy, the Environment and Water (2021). Our overall aim was to answer the question: How many of the 21 priority listed plant species survived and/or recruited after the 2019–2020 wildfires and was survival linked to estimated local fire severity? We developed and tested the effectiveness of a rapid method of documenting post-wildfire survival and distribution. We use this method to score basic biological and ecological information and conduct rapid monitoring of short-term survival and growth rates for suitable populations (100+ individuals). Additionally, we collected baseline observational records of insects and other invertebrates found on the target species to inform future research on ecological interactions that potentially influence the persistence of species populations. Published research on all these 21 species is extremely limited, including knowledge of wildfire impacts, population sizes and ecological interactions such as pollination and herbivory that potentially affect population persistence and survival. We combine our data with previous knowledge and assumptions about the ecology and wildfire responses of each species (see Appendix S1) and classify a rarity score for each using the Rabinowitz (1981) framework. Our results contribute new information on understudied rare and threatened species that will be valuable for management and monitoring guidelines.

METHODS

Study region

The New England Batholith of eastern Australia has multiple regions of high floristic endemism and species rarity often associated with old climatically buffered infertile landscapes (OCBILs) (Hopper et al., 2021; Hunter & Clarke, 1998). The Torrington State Conservation Area (SCA) (30 052 ha) and adjacent Bolivia Hill Nature Reserve (NR) (1782 ha) protect two proximate areas of woodland, heath and granite outcrops that include many rare species (Figure 1). This region is characterized by highly heterogeneous landscape mosaics, where habitat suitability for a species can change at very small spatial scales (i.e., centimetres to metres) (Clarke, 2002). For most species endemic to the batholith, there is little knowledge of their ecology, demography and population status and most existing information requires verification (Clarke et al., 1998; Hunter, 2002). The entire area of Torrington SCA was impacted by the 2019–2020 megafire event, with local burn impacts varying from unburned, moderately burned or severely burned at small spatial scales (Figure 1). Bolivia Hill NR was not affected in the 2019–2020 megafires (last recorded major wildfire event in 2002) at time of writing.

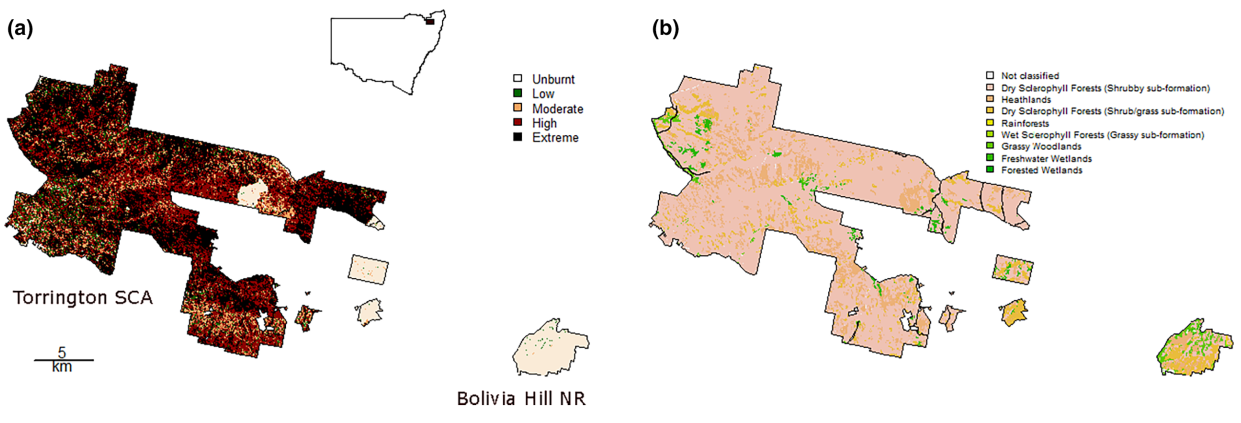

FIGURE 1 Map of Torrington State Conservation Area and Bolivia Hill Nature Reserve showing (a) fire extent and severity of the 2019 wildfires and (b) vegetation classes. Inset shows the geographical location within New South Wales. *Data sources*: State Government of NSW and Department of Planning, Industry and Environment (2020) and State Government of NSW and Department of Planning and Environment (2022).

Survey method

In October 2020, 11 months after the Torrington wildfire in November 2019, we commenced a rapid assessment of 21 priority listed plant (Department of Climate Change, Energy, the Environment and Water, 2021), along with additional rare taxa known to occur in similar environments. The following 21 species were targeted: *Acacia pubifolia* Pedley, *Acacia pycnostachya* F.Muell. ex Benth., *Acacia torringtonensis* Tindale, *Acacia williamsiana* J.T.Hunter, *Almaleea cambagei* (Maiden & Betche) Crisp & P.H.Weston, *Boronia boliviensis* J.B.Williams & J.T.Hunter, *Boronia granitica* Maiden & Betche, *Boronia inflexa* ssp. *torringtonensis* Duretto, *Brachyloma saxicola* J.T.Hunter, *Callistemon pungens* Lumley & R.D.Spencer, *Cassinia heleniae* Orchard, *Eucalyptus boliviana* J.B.Williams & K.D.Hill, *Hakea macrorrhyncha* W.R.Barker, *Homoranthus binghiensis* J.T.Hunter, *Homoranthus croftianus* J.T.Hunter, *Homoranthus lunatus* Craven & S.R.Jones, *Kardomia odontocalyx* (A.R.Bean) Peter G.Wilson, *Monotaxis macrophylla* Benth., *Persoonia terminalis* ssp. *terminalis* L.A.S.Johnson & P.H.Weston, *Prostanthera teretifolia* Maiden & Betche and *Thesium australe* R.Br. A total of 13 of the species are listed as either endangered or vulnerable on the NSW Biodiversity Conservation Act 2016 (BCA Act) and/or the federal Environmental Protection and Biodiversity Act (EPBC Act). *Boronia boliviensis*, *B. granitica* and *B. inflexa* ssp. *torringtonensis* may now be recognized in the genus *Cyanothamnus* (Duretto et al., 2020), but we will use *Boronia* in this paper to align with the priority list the project was funded under.

To locate populations of target threatened species, we used adaptive meanders (similar to adaptive line transects, or 'Pollard walks', of Pollard et al. (2002) used for butterfly sampling). Walks follow a non-linear path in response to topography and habitat conditions, with an expert observer maintaining a steady pace and looking within a buffer of approximately 15 m (or line of sight) on each side of the navigated path for target species and suitable habitat. When a species or likely habitat is sighted, the observer leaves the path to search the likely habitat, confirm the species' location and relevant information and then continues along the navigated path direction. The method is designed to cover as many locations and populations as possible with limited time and resources. Many of the target taxa were known to be restricted to granite outcrops and rock pavements (Bean, 1997; Clarke et al., 1998; Hunter, 1997a, 1997b; Hunter, 1998a,1998b; Hunter & Clarke, 1998; Hunter & Copeland, 2001; Hunter & Williams, 1994; Williams & Hunter, 2006) while others were associated with intermediate or other landscape features. Similarly, *A. cambagei* is known largely from wetland areas (Clarke et al., 1998). Given the known preference of some target taxa for these habitats, the adaptive meanders prioritized rock pavements, outcrops and wetlands within the vicinity of the search paths; however, all habitats between target habitats were included in searches. In total, 20 adaptive meanders were undertaken across the range of environments found within the reserves between October 2020 and July 2021. All walks were led by JTH, an expert botanist with decades of experience working closely with the target species, who is highly skilled in being able to identify the target species in situ.

Once a population was found, a maximum of 5–10 min was spent recording rapid visual estimates of population size, population age, health and phenology. We used the free mobile and web application Epicollect5 (Aanensen et al., 2014) to enable mobile phone-based data collection and collected data from each location with the following main fields: date; location (latitude-longitude and easting-northing, with location error in meters recorded); taxa; estimated population size (<10, 10–50, 50–100, 100–500, 500–1000, 1000 plus); population age (mainly adults, mixed stand, mainly juveniles); phenology of the entire population (non-reproductive, largely not reproductive, few flowers, mostly flowering, flowers and fruit, mainly fruit); health (healthy, mixed, unhealthy, many dead); visual estimates of wildfire severity at the precise location (unburnt, scorch to 1 m, scorch 1–5 m, scorch 5–10 m, scorch >10 m, crown fire). Population size and age were estimated with a rapid visual count. Phenology and health were rapidly assessed using visual estimates of proportion of individuals and individual branches with flowers or fruits and/or obvious signs of herbivory or other factors affecting health (e.g., dieback). Populations were considered different if there was a clear and distinct discontinuity between patches; however, this was different for different species. For example, the highly restricted rock outcrop species had clear disjunctions, whereas other species such as *P. terminalis* ssp. *terminalis* were largely scattered individuals. As a general rule, if several hundred meters were passed without seeing any more individuals of the species it was considered the population had a defined boundary.

Monitoring

To gather additional ecological information on some target species, we established 11 monitoring sites covering 16 species across Torrington SCA (nine sites) and Bolivia Hill NR (two sites) (Appendix S3). These sites were a combination of known locations and new sites identified through adaptive meanders and were limited to sites where at least 100 individuals were counted. Baseline monitoring was established in October–early December 2020 for 10 species and additional sites for the remaining six species were established from late January to early April 2021 as populations of other species were found during adaptive meanders. Most species ($n = 14$) were monitored at least twice: the first monitoring was conducted October 2020–February 2021 (austral late spring–summer) and the second monitoring in May 2021 (austral late autumn-winter). Populations of two species (*E. boliviana* and *B. inflexa* ssp. *torringtonensis*) were only monitored once due to being discovered later in the study period and logistical issues that prevented a second monitoring, including COVID-19 restrictions, a short funding period and adverse weather events that prevented access to Torrington SCA during austral summer 2020–2021. At each site, at least 100 individuals of the target species were tagged for monitoring. Most populations occurred within very small patches of suitable habitat and often with high densities. For small populations (100–200 individuals), all or most of the individuals were tagged. For larger populations, individuals were tagged haphazardly (taking into account safety and minimizing plant damage) until the target number was reached. Each individual was given a unique ID. On each monitoring visit (except for 5 populations that only have data for one monitoring visit; see Appendix S3) we measured the height (cm) of each tagged plant and gave it a health score. Health was scored from 0 to 5, where 0 is dead and 5 is a thriving individual and scores of 2–4 were based on proportion of leaves lost from the plant due to herbivory or dieback. During monitoring, any insects observed interacting with the target species were photographed and the nature of the interaction or behaviour (e.g., pollination, herbivory, nesting or sheltering) was documented.

Data analysis

All analyses and figures were produced in R 4.2.3 (R Core Team, 2023). Since we were focused on rapid documentation of previously unrecorded populations and biological and ecological information of understudied species, replication across categories is highly variable (Appendix S2). Our data analysis is hence focused on potential associations to identify avenues for future research, rather than identifying causal relationships.

To assess the influence of wildfire on our target species, we first collated data on fire history (covering the period 1920–2020) from the NPWS Fire History—Wildfires and Prescribed Burns dataset (State Government of NSW and Department of Planning and Environment, 2010). To determine fire history for each recorded population, we used the *terra* package (Hijmans et al., 2023) to intersect fire frequency (number of fires between 1920 and 2020) with every point coordinate for each population found during the rapid meander surveys. All Bolivia Hill populations experienced only one recorded fire during the data period (which occurred in 2002) and the location was not affected by the 2019–2020 wildfires. All Bolivia Hill species are endemic to that reserve and populations of those species skewed analyses when we analysed all data together, so the fire history and severity analyses focused on Torrington populations only (all data for all species is available in Appendix S2).

To explore associations between population variables (population size and population age) and fire variables (estimated fire severity and fire frequency) for each population detected during the meander surveys (Appendix S2), we created facet plots using *ggplot2* (Wickham, 2016).

To classify each species' rarity (all species from Torrington and Bolivia Hill), based on existing knowledge and the new information collected in surveys, we used the protocol developed by Rabinowitz (1981) for defining eight types of rarity based on three classes of variables: geographic range, habitat specificity and local population size (information provided in Appendix S1).

To assess the short-term growth rate and survival for all monitored species, we calculated the percent survival and change in individual height between the first and last monitoring event (information provided in Appendix S3).

RESULTS

General patterns

The total length of adaptive meanders was approximately 409 km with an estimated search area of 1226 ha (based on the visible search path of 30 m). These surveys located 1308 populations (Appendix S2). All of the target species, except *T. australe*, were found during the survey period (October 2020–July 2021). Estimates of population sizes varied across the target species (Figure 2, Appendix S2). For example, only two individuals of *C. pungens* were found, while populations of less than 5000 individuals each, across their entire distribution within the reserves, were found for *B. inflexa* ssp. *torringtonensis*, *E. boliviana*, *B. boliviensis*, *C. heleniae* and *H. croftianus* (Figure 2). Other taxa, such as *K. odontocalyx* and *A. torringtonensis*, were estimated to have extremely abundant populations of more than 200 000 individuals within the reserves (Figure 2, Appendix S2).

Species with populations that occurred within the general matrix of woodland and forest vegetation (Appendix S1) were largely burnt during the 2019–2020 megafires and were represented by non-reproductive juvenile populations (e.g., *A. torringtonensis*, *A. cambagei*, *B. granitica*, *B. inflexa* ssp. *torringtonensis*, *H. macrorrhyncha*). Those with populations largely restricted to rock pavements often escaped being burnt, with most populations remaining as mature age stands (e.g., *H. binghiensis*, *K. odontocalyx*) (Appendix S1).

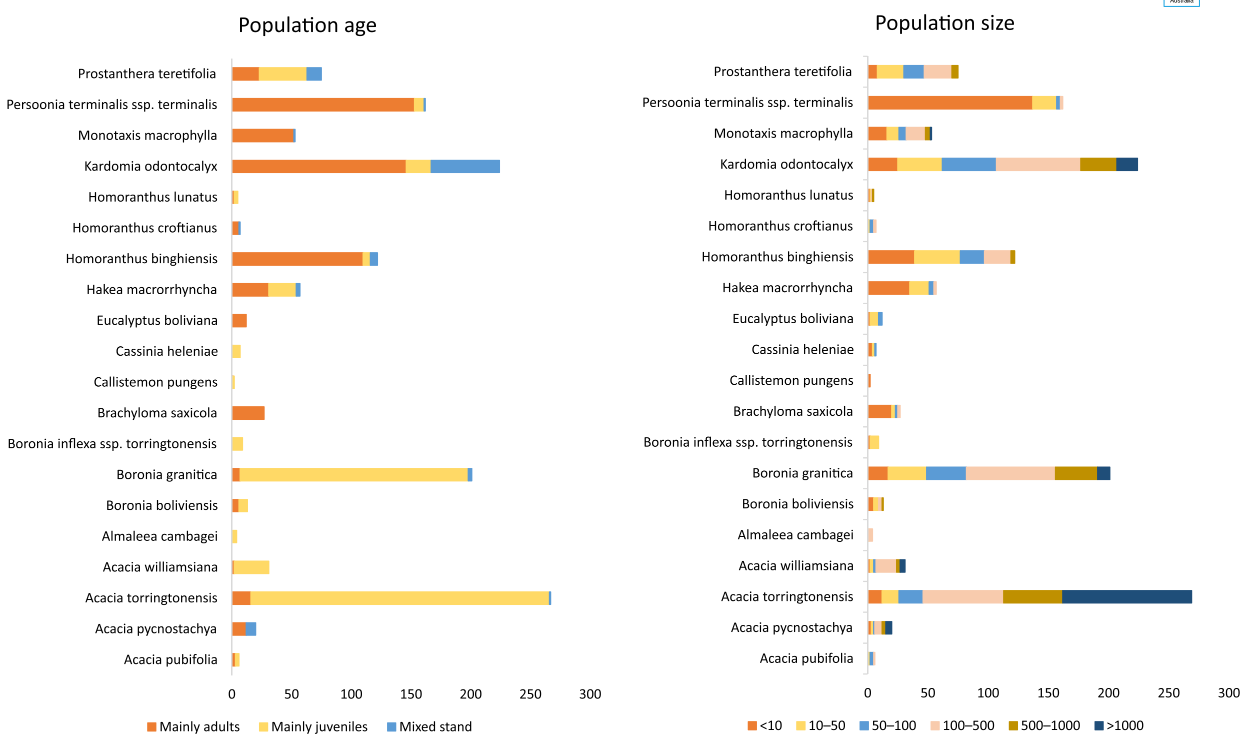

FIGURE 2 Population age and size distribution for all target species. *Thesium australe* is not included as it was not found. Full data is available in Appendix S2.

Brachyloma saxicola was the only species found in both Torrington SCA and Bolivia Hill NR (4 out of 26 populations were located at Bolivia Hill). Target species within Torrington SCA often showed a distinct east or west distributional preference (Appendix S1). *Acacia pubifolia*, *H. binghiensis*, *K. odontocalyx*, *M. macrophylla* and *P. terminalis* ssp. *terminalis* are largely or solely restricted to the western half of the Torrington SCA, while *A. cambagei*, *B. inflexa* ssp. *torringtonensis*, *B. saxicola*, *Cassinia helaniae*, *H. macrorrhyncha*, *H. lunatus* and *P. teretifolia* are solely or largely restricted to the eastern half of the reserve. *Boronia granitica* and *A. torringtonensis* were common throughout, though with larger and more populations towards the west.

Fire history and megafire effects

All species' populations located within Torrington SCA experienced the 2019 wildfire and only 50 (out of 1308) populations had not experienced a recorded fire prior to this (Figure 3, Appendix S2). More than half of populations (54%) experienced two fires, that is, only one other fire prior to 2019 and 40% experienced three fires. Few populations (7.5%) had experienced a prescribed burn as well as wildfires. Populations that only experienced prescribed burns prior to the 2019 wildfire ($n = 53$) were predominantly of *P. teretifolia* and *K. odontocalyx* (Appendix S2).

Acacia species, *Boronia* species and *P. teretifolia* were generally more abundant as juveniles in severely burned areas and a high number of extant adult populations of *K. odontocalyx*, *H. binghiensis* and *P. terminalis* ssp. *terminalis* were largely found in unburnt areas (Figure 3, Appendix S2).

We classified 10 of the 21 total species as having the highest rarity classification (small distribution, scarce population size) and most of the

FIGURE 3 Relationships between population age (left panels) and population size (right panels) and the estimated fire severity at each site (top row) and historical fire frequency (bottom row). Dots represent populations of each target species detected during the meander surveys; dots may be overlapped where multiple populations fit the same combination of attributes, so the number of visible dots in each species panel does not necessarily indicate the number of detected populations (see Appendix S2 for full data).

remaining species as having small distributions and high population size (Table 1, Appendix S1). Two species, *T. australe* and *M. macrophylla*, were given the least rare classification, having large distributions and high population sizes (Table 1).

Monitoring of short-term survival and growth rates

A total of 2299 individuals across 14 species were monitored at least twice and 200 individuals across two species were tagged and measured for monitoring once (Table 2, Appendix S3). *Monotaxis macrophylla*, a short-lived fire ephemeral, had the lowest calculated survival rate, with only 3 of the tagged 100 individuals surviving at the second monitoring period (Table 2). All other species had survival rates between 59% and 100% of tagged individuals and a median change in height across the monitoring period between 3.6% and 100%, with some species showing high variation in growth rates (Table 2).

Ecological interactions

Plant–insect interactions were observed for nine of the target species, with most interactions previously undocumented in published literature

TABLE 1 Rarity classes of select targeted species from the Torrington SCA and Bolivia Hill NR after Rabinowitz (1981).

Geographic distribution	Large		Small	
Population size	**High**	**Scarce**	**High**	**Scarce**
Habitat specificity				
Broad	*Thesium australe* (V, V*)		*Acacia torringtonensis*	*Persoonia terminalis* ssp. *terminalis*
			Boronia granitica (V, E*)	
			Acacia pycnostachya (V, V*)	
Restricted	*Monotaxis macrophylla* (E)		*Acacia williamsiana*	*Acacia pubifolia* (E, E*)
			Brachyloma saxicola	*Almaleea cambagei* (V, E*)
			Callistemon pungens subsp. *pungens* (V)	*Boronia boliviensis* (E*)
			Homoranthus binghiensis (E*)	*Boronia inflexa* ssp. *torringtonensis* (CE*)
			Kardomia odontocalyx	*Cassinia heleniae*
			Prostanthera teretifolia	*Eucalyptus boliviana* (V*)
				Hakea macrorrhyncha
				Homoranthus croftianus (E*)
				Homoranthus lunatus (V, V*)

Note: Assessment is based on overall known distribution, existing knowledge and data collected in this study (Appendix S1). Endangered (E) and vulnerable (V) under the Commonwealth *EPBC* Act; critically endangered (CE*) endangered (E*) and vulnerable (V*) under the NSW *BCA* Act.

TABLE 2 Survival rate and average growth rate of monitored species.

Species	Total no. tagged individuals (number of populations)	Total no. monitored at least twice	Location	Median baseline height (cm) (IQR)	Survival rate (% tagged individuals)	Median % change in baseline height (IQR)[a]	Median growth rate (cms per day) (IQR)[a]
Acacia pubifolia	200 (1)	100	Torrington	55 (15, 300)	98	11.11 (−5.4, 30.1)	0.02 (−0.008, 0.04)
Acacia pycnostachya	100 (1)	100	Bolivia Hill	227.5 (180, 300)	100	3.6 (−2.3, 10.5)	0.05 (−0.03, 0.19)
Acacia torringtonensis	399 (4)	399	Torrington	40 (31, 66)	98	40.7 (7.6, 67.6)	0.07 (0.02, 0.12)
Acacia williamsiana	100 (1)	100	Torrington	45 (34, 56)	100	6.3 (0.33, 18.5)	0.03 (0.002, 0.1)
Boronia boliviensis	100 (1)	100	Bolivia Hill	20 (13, 25)	100	59.8 (40.8, 74.7)	0.11 (0.07, 0.13)
Boronia granitica	200 (2)	200	Torrington	12 (8, 17)	59	87.1 (54.4, 134.1)	0.06 (0.03, 0.09)
Boronia inflexa ssp. *torringtonensis*	100 (1)	0	Torrington	14 (10, 20)	~	~	~
Eucalyptus boliviana	100 (1)	0	Bolivia Hill	525 (350, 737.5)	~	~	~
Homoranthus binghiensis	200 (2)	200	Torrington	105 (71, 135)	100	9.7 (2.5, 17.6)	0.05 (0.01, 0.09)
Homoranthus croftianus	100 (1)	100	Bolivia Hill	127.5 (100, 155.8)	99	10.9 (5.3, 17.2)	0.07 (0.04, 0.1)
Homoranthus lunatus	100 (1)	100	Torrington	4.5 (3.5, 6)	90	100 (43.5, 128.6)	0.03 (0.02, 0.04)
Hakea macrorrhyncha	100 (1)	100	Torrington	14 (12, 16)	85	41.7 (24.9, 59.5)	0.03 (0.02, 0.05)
Kardomia odontycalyx	399 (4)	399	Torrington	47 (27, 79)	98	20 (1.2, 45.8)	0.04 (0.002, 0.11)
Monotaxis macrophylla	100 (1)	100	Torrington	42.5 (27, 61)	3	−31.0 (−42.3, −30.9)	−0.09 (−0.11, −0.09)
Prostanthera teretifolia	200 (2)	200	Torrington	39 (25.3, 70)	98	8.8 (0, 22.2)	0.03 (0, 0.06)
Persoonia terminalis ssp. *terminalis*	100 (1)	100	Torrington	109 (81.3, 130)	100	9.9 (4.8, 18.1)	0.05 (0.03, 0.09)

Note: Data show median values with interquartile range (IQR) in brackets. See Appendix S3 for full monitoring dataset (locations removed).

[a]Calculated based on surviving individuals only.

(Appendix S4). Around a third of interactions involved Coleoptera (31%), which could be potential herbivores of the plants and multiple Hymenoptera, Coleoptera and Diptera species exhibited flower-visiting behaviour (Appendix S4). Four observations documented likely pollination of open flowers by an insect species: *M. macrophylla*—two separate native bee species (Halictidae) and a beefly (Bombyliidae: Villiini); *P. terminalis*—a native bee (Megachilidae).

DISCUSSION

Extreme wildfires are increasingly common globally in response to rapid environmental change and are largely driven by climate change, fire management and suppression and land use change. More frequent extreme fires are a severe threat to vulnerable plants and vegetation communities (DellaSala et al., 2022; Le Breton et al., 2022) and effects can be even more severe in combination with other climate-related stressors such as drought (Walden et al., 2023). Limited knowledge of the basic ecology of most species and lack of data on occurrences and population sizes of vulnerable species, are key obstacles to species recovery and conservation actions in response to wildfire events (Gallagher et al., 2021).

Our combination of targeted site-based monitoring and adaptive meander survey techniques, while collecting a range of demographic, distributional and phenological information, has greatly enhanced basic knowledge of our target species. The field observations contribute new knowledge of life history, population size, distribution and response to wildfire for target taxa (Appendix S1), reveal a previously undocumented pattern in species distribution within the Torrington SCA and identify new plant–insect interactions, especially pollination, that warrant further investigation. These results highlight how rapid on-ground surveys after major wildfire events are extremely valuable for identifying new records of threatened species and revealing ecological knowledge to inform conservation planning. We strongly recommend that appropriate funding and resources be available to deploy on-ground surveys immediately after major disturbance events to collect valuable time-sensitive data.

Increased knowledge of priority species

Species growing on rock pavements and associated with outcrops were more likely to escape the extensive wildfires, which were classed as catastrophic (total crown consumption and subsequent overstory death; Figure 1; State Government of NSW and Department of Planning, Industry and Environment, 2020) in many areas of the Torrington SCA. All of these species were found to be obligate seeders when burnt populations were found (Appendix S1). Populations of rock pavement endemics were dominated by mature reproductive individuals with similar population sizes pre- and post-fire (Appendix S1). This finding aligns with previous investigations which highlight rock pavements as fire refugia allowing for the evolution of fire-avoidant narrow endemics within a pyric landscape (Fitzsimons & Michael, 2017; Hunter, 2017; Watson & Wardell-Johnson, 2004). Taxa growing within close proximity to rock pavements and within dense boulder fields were also found to be obligate seeders (e.g., *A. torringtonensis* and *B. granitica*) and also were often found to experience a lower wildfire severity than in the adjacent open forest and woodlands. Increased heterogeneity in forest structure, including from rocky pavements and boulder fields, can reduce fire severity (Koontz et al., 2020) and provide more refugia for some plant species compared to more open wet habitats (Hylander & Johnson, 2010). Further research on how the heterogeneous habitats across Torrington and Bolivia Hill influence fire paths and severity would provide valuable insight for management plans.

Species found within the surrounding matrix of forests, woodlands and wetlands (e.g., *C. heleniae* and *A. cambagei*) responded to fire by resprouting or showed a mixed response of resprouting under lower severity wildfire and seeding under a higher severity (Appendices S1 and S2). Some taxa responded with mass germinations post-wildfire but have almost no current reproductive mature individuals based on on-ground estimations (e.g., *A. torringtonensis*, *B. granitica* and *H. lunatus*), suggesting that most mature individuals were destroyed in the wildfire. These populations, where individuals are almost entirely juveniles, will be vulnerable for some time to extreme drought or recurrent wildfires until adulthood and subsequent replenishment of seed banks (Croft et al., 2010). *Cassinia heleniae* and *H. macrorrhyncha* are two species that appear to have not recruited sufficiently post-wildfire (at the time of survey) and may have current populations that are lower than pre-wildfire estimates, based on the number of standing dead compared to seedling recruitment (Table 2, Appendices S1 and S2). Historical records and publications along with a lack of recruitment found during this survey (Table 2, Appendix S1) suggest *Brachyloma saxicola* and *C. pungens* ssp. *pungens* may have reduced in population size within Torrington SCA (Clarke et al., 1998; Hunter & Clarke, 1998).

The number of recorded fires (including the 2019 wildfire) that most detected populations experienced in the previous 100 years was generally low (three or less) and very few populations had experienced prescribed burns. Populations that only experienced the 2019 megafires were more likely to be mixed stands of adults and juveniles. In the absence of data, fire responses have historically been assumed for many of the target species based on general ecological principles or responses of other species, so our data provide a valuable foundation for further analyses of how fire severity, frequency and management impact these species. All of Torrington SCA is now classified as either 'vulnerable to frequent fire' or 'too frequently burnt' (Department of Planning Industry and Environment, 2021), meaning all populations of target species are under significant threat from any additional fire events and the ecological impact of future wildfire risks in this region requires urgent attention.

Bolivia Hill NR and Torrington SCA are known as areas of high local endemism (Hunter & Clarke, 1998; Quinn et al., 1995). Our survey revealed an important observation that has not been recognized previously, that is, the Torrington batholith has eastern and western sub-regions of endemism (see Appendix S1). Some local endemic taxa are largely or wholly restricted to the western parts of the batholith, such as *H. binghiensis*, *K. odontocalyx* and *P. terminalis* subsp. *terminalis*. Other taxa, while not restricted to the batholith, only occur in western areas (e.g., *A. pubifolia*). A number of endemics only occur in the eastern section of the batholith such as *B. inflexa* ssp. *torringtonensis*, *C. heleniae* and *P. teretifolia* along with non-endemics such as *B. saxicola*. It is possible that this variation is influenced by subtle changes in climate, geologies or land use histories (Clarke et al., 1998) or different fire histories (State Government of NSW and Department of Planning and Environment, 2010) and further research is needed to identify the processes that drive this spatial pattern. This important observation will have implications for conservation within Torrington SCA, as the east and western parts of the batholith will likely require different management actions and planning for translocations or changing climates.

Conservation listings

Our observations also highlight that a species' conservation listing (or lack thereof) may not match its actual population ecology or threat status. Based on our observations and Rabinowitz's (1981) rarity classes, it is likely that 10 of our target taxa are of the rarest type, being limited in geographic distribution, restricted habitat specificity and scarce population sizes. Of these, only seven have been listed under state or Commonwealth legislation (Table 1). The remaining two (*C. heleniae* and *H. macrorrhyncha*) are not listed on either Act, but are currently known from only a few hundred individuals and their threat status should be urgently assessed. While *P. terminalis* ssp. *terminalis* has broader habitat tolerances than the previous taxa it does not occur in large numbers, does not generally occur on fire refugial rock platforms and has a very diffuse population. It is an obligate seeder with a comparatively low estimated total population size due to these features. Hence, we suggest that all taxa classified as having small geographic distribution (i.e., the right-hand column of Table 1) should be listed on both Acts to increase support for prioritized research and conservation actions. The two most widespread taxa with potential high population sizes in known locations outside of the study area are both currently listed, with *T. australe* as vulnerable on both the *BCA* and *EPBC* Acts and *M. macrophylla* as endangered on the *BCA* Act and their potential for delisting could be assessed. *Monotaxis macrophylla* is a short-lived fire ephemeral occurring in protected areas, which increases its potential for delisting (Bell, 2021).

Ecological interactions

In addition to highlighting the variability in growth rates among and within species, our on-ground local monitoring also revealed valuable new information on plant–insect interactions for some of our target species, which would not have been documented through large-scale remote mapping or spatial analyses. There is very little published knowledge of the ecology of most of Australia's threatened plant species, including those on our target list. Basic ecological knowledge, for example, about pollination vectors, plant–soil interactions, common herbivores and other community interactions, is not available for our target species, yet this information is often critical to the success of conservation and management strategies. Our observations document new information (Appendix S4) that provide a valuable foundation for further observational and experimental studies to confirm the effects of documented and potential interactions. For example, we observed likely pollination by native bees and flies on two species (*M. macrophylla* and *P. terminalis* ssp. *terminalis*) for which there is no published information on pollination vectors. We also observed two beetle species, a beefly, a native bee and ants visiting flowers (and potentially acting as pollinators) on *K. odontocalyx* and a beetle species visiting flowers of *B. granitica*. Other observations included beetles that may potentially impact plant health through feeding behaviour (e.g., Chrysomelinae sp. and Acacia longhorn beetle, *Penthea solida*, on *A. torringtonensis* plants) (Appendix S4).

Knowledge of ecological interactions is unknown for most plant species of conservation concern and we particularly highlight pollination and plant–soil interactions as key interactions that require urgent attention to improve conservation success for rare and threatened species in the study region, as these have direct impact on reproductive success, seed banks and wildfire responses of plant species.

Value and limitations of methods

Our combination of broadscale on-ground searches and site-based monitoring was effective in achieving our project goals, which were to locate surviving populations of our target species after the catastrophic 2019–2020 megafires and to increase basic ecological and biological knowledge of those species. Expert-led adaptive meanders were effective in covering large areas of the study sites in short periods of time, ensuring detection of all but one of our target species. The only species that was not located (*T. australe*) is an obligate root parasite for which species/host associations are unclear (Doyle & Pellow, 2018) and further research is needed to identify environmental parameters that support *T. australe* population detection. The combined meander and monitoring techniques significantly increased the basic ecological and biological knowledge of all detected target species. Historically, research has not been undertaken for most of these species. Published knowledge is largely limited to the initial descriptions of the species and some basic knowledge of habitat associations. Therefore, the data we publish here, based on adaptive meanders surveys and subsequent monitoring at selected sites, provides valuable new information to support further research on the biology and ecology of these rare species surviving in a unique hotspot of endemism.

Our method is logistically simple and rapid and easily adapted to other systems and taxa, providing a valuable opportunity to address major knowledge gaps in understudied systems as extreme wildfires and megafires increase globally. The main limitations to the future deployment of this approach will be funding and available expertise. The success of our method could have been influenced by the botanical expertise of the lead surveyor (JTH), who has decades of experience working explicitly on the flora of the study region, including most of the target species and is highly experienced in identifying the species in the field at all life stages. Plants sometimes lack key taxonomic features needed for confident in situ identification, making field experience valuable, particularly for recognizing non-reproductive individuals, such as seedlings or adults outside their flowering seasons. However, the 'botanist effect', where experts are assumed to detect more species than non-experts (Ahrends et al., 2011), may be context-dependent and could be more influenced by observation time or a surveyor's familiarity with the ecosystem (Morrison, 2016; Perret et al., 2023). To enhance detection rates and efficiency, future post-disturbance surveys would ideally require participation by expert botanists, either as survey leaders or as trainers for other observers and there is scope for further work on exploring how expertise influences detection rates in these unique systems (e.g., McCarthy et al., 2013).

CONCLUSION

We have been able to significantly increase our knowledge of the ecology, wildfire responses and population sizes of 21 rare and threatened plant species affected by the 2019–2020 megafires in northern New South Wales. In addition, we have revealed previously undocumented distribution patterns and ecological interactions for these species that warrant further investigation and will inform future management strategies for rare and restricted species associated with rocky outcrop landscapes. Our results highlight the value of post-disturbance rapid on-ground surveys for informing long-term conservation outcomes for rare and threatened taxa.

AUTHOR CONTRIBUTIONS

Manu E. Saunders: Conceptualization (equal); data curation (equal); formal analysis (equal); funding acquisition (equal); investigation (equal); methodology (equal); project administration (equal); resources (equal); supervision (equal); validation (equal); visualization (equal); writing – original draft (equal); writing – review and editing (equal). **Rose L. Andrew:** Conceptualization (equal); data curation (equal); formal analysis (equal); funding acquisition (equal); investigation (equal); methodology (equal); resources (equal); writing – review and editing (equal). **James Mitchell-Williams:** Data curation (supporting); formal analysis (supporting); investigation (supporting); methodology (supporting); writing – review and editing (supporting). **Peter Pemberton:** Data curation (supporting); formal analysis (supporting); methodology (supporting); writing – review and editing (supporting). **Elizabeth M. Wandrag:** Conceptualization (equal); formal analysis (equal); funding acquisition (equal); investigation (equal); methodology (equal); writing – review and editing (equal). **John T. Hunter:** Conceptualization (equal); data curation (equal); formal analysis (equal); funding acquisition (equal); investigation (equal); methodology (equal); project administration (equal); resources (equal); supervision (equal); writing – original draft (equal); writing – review and editing (equal).

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

All threatened species survey results are submitted to NSW BioNet. Summary survey and monitoring data are available online with this paper with species and site coordinates removed to protect locations of threatened species.

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SUPPORTING INFORMATION

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