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Forest Fire Severity and Koala Habitat Recovery Assessment Using Pre- and Post-Burn Multitemporal Sentinel-2 Msi Data

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Abstract: Habitat loss due to wildfire is an increasing problem internationally for threatened animal species, particularly tree-dependent and arboreal animals. The koala (*Phascolartos cinereus*) is endangered in most of its range, and large areas of forest were burnt by widespread wildfires in Australia in 2019/2020, mostly areas dominated by eucalypts, which provide koala habitats. We studied the impact of fire and three subsequent years of recovery on a property in South-East Queensland, Australia. A classified Differenced Normalised Burn Ratio (dNBR) calculated from pre- and post-burn Sentinel-2 scenes encompassing the local study area was used to assess regional impact of fire on koala-habitat forest types. The geometrically structured composite burn index (GeoCBI), a field-based assessment, was used to classify fire severity impact. To detect lower levels of forest recovery, a manual classification of the multitemporal dNBR was used, enabling the direct comparison of images between recovery years. In our regional study area, the most suitable koala habitat occupied only about 2%, and about 10% of that was burnt by wildfire. From the five koala habitat forest types studied, one upland type was burnt more severely and extensively than the others but recovered vigorously after the first year, reaching the same extent of recovery as the other forest types. The two alluvial forest types showed a negligible fire impact, likely due to their sheltered locations. In the second year, all the impacted forest types studied showed further, almost equal, recovery. In the third year of recovery, there was almost no detectable change and therefore no more notable vegetative growth. Our field data revealed that the dNBR can probably only measure the general vegetation present and not tree recovery via epicormic shooting and coppicing. Eucalypt foliage growth is a critical resource for the koala, so field verification seems necessary unless more-accurate remote sensing methods such as hyperspectral imagery can be implemented.

Keywords: forest; wildfire; koala; habitat; Sentinel-2; dNBR

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1. Introduction

Habitat loss due to anthropogenic impacts and climate-induced effects including wildfires is becoming an increasingly serious problem internationally for threatened animal species [1,2]. Tree-dependent and arboreal animals are at risk of displacement. Examples include the African Forest Elephant (*Loxodonta cyclotis*) [3]; the Woodland Caribou in Canada [2], the Mount Graham Red Squirrel in the USA (*Tamiasciurus hudsonicus grahamensis*) [4] if fires increase in scale, the Giant Noctule in Europe (*Nyctalus lasiopterus*) [5], and in Australia, the Koala (*Phascolartos cinereus*) [6]. Koalas are a threatened species mainly because of habitat loss from clearing and fire, but also because of drought, predators and disease [3]. Although koalas are arboreal, they are not as mobile as some other arboreal animals when they need to escape from a wildfire. Birds are able to fly to safety, and some Australian arboreal mammals can glide between trees, such as the Greater Glider (*Petauroides volans*), while some mammals can move between tree canopies, such as some monkeys [7]. The koala, however, usually has to climb down from a tree and move across the ground to move to other trees [8]. Dense shrub layers and undergrowth can make

traversal difficult and expose koalas to predators, particularly dogs. This probably makes them more vulnerable to fires than many other arboreal species.

Large areas of Australian forests were burnt by widespread wildfires in Australia in 2019/2020 [9–11]. These fires were preceded by drought [12], which likely increased the flammability of these forests [13]. Most of these forests and woodlands are dominated by eucalyptus trees, which provide habitats for the koala (*Phascolarctos cinereus*); hence, these fires potentially impacted large areas of their habitats, a phenomenon that occurs across much of Eastern Australia [14]. Shabani et al. [15] found that nearly 40% of the total koala habitat in Australia has a high or very-high fire susceptibility rating and predicted that this figure will increase to nearly 45% by 2070 due to climate change. Eucalypt forests can burn at frequent intervals (for example, annually) depending on climatic conditions and anthropogenic activities [16]. If these fires increase in intensity and frequency, then the koala will be at increased risk.

The recovery responses of eucalypt communities have the potential to significantly affect the suitability of habitats for koala populations [17]. Many eucalypts can recover by means of epicormic shooting on the stems and/or coppicing from the base of the trunk, which are both parts that are edible for koalas. If the fire intensity is too severe, then this will result in top kill [16], but the root system can survive and subsequently be coppiced. Although the most widespread severe fires of 2019/2020 in Australia occurred in the states of New South Wales (NSW) and Western Australia, severe fires were also widespread in Victoria and Queensland [13]. The koala habitat in South-East Queensland (SEQ) was therefore also impacted by the fire in 2019/20 [18], and the recovery of that habitat was found to vary with fire severity [18]. Koalas are known to utilise a variety of different eucalypt-dominated forest types in Queensland, Australia; these fine-scale differences are mapped as Regional Ecosystems (REs; Queensland Department of Environment and Science) [19]. Each RE is defined by a descriptive code consisting of three numbers, which denote biogeographical region, broad geomorphological unit (land zone) [20], and unique vegetation type, respectively (e.g., 12.8.16; Table 1).The post-fire recovery of eucalypt forests has been found to vary with forest type, and this is influenced by the varying post-fire responses of the constituent tree species [18,20–22]. The efficacy of these responses will affect habitat availability for koalas. Koala habitat mapping [14] has been used to identify the primary koala habitat REs (Supplementary Table S1).

Table 1. Regional Ecosystems observed within the study area that are koala habitats and were analysed in this study. * BVG = Broad Vegetation Group at 1:1,000,000 map scale [19]. Upland REs are listed first, followed by alluvial REs. Sample numbers are from the total of 88 plotless sample sites.

Regional Ecosystem Code	Forest Type Analysis Code	Short Description (QDES 2023b) and Comments	Common Names of Dominants	Landscape	BVG1 m *	Number of Samples
12.12.12	IPR	*Eucalyptus tereticornis, Corymbia intermedia, E. crebra* +/− *Lophostemon suaveolens*—woodlands on Mesozoic to Proterozoic igneous rocks.	ironbark and pink bloodwood	granite ridges	9 g	9
12.12.23	GBS	*Eucalyptus tereticornis* subsp. *tereticornis* or *E. tereticornis* subsp. *basaltica* +/− *E. eugenioides*—woodlands on crests, upper slopes, and elevated valleys and plains on Mesozoic to Proterozoic igneous rocks.	stringybark and mountain blue gum	granite hills	9 g	66
12.8.16	IBM	*Eucalyptus crebra* +/− *E. melliodora, E. tereticornis*—woodlands on Cainozoic igneous rocks.	blue gum and ironbark	basalt hills	11 a	8
12.3.3	BFA	*Eucalyptus tereticornis*—woodlands and open forests on alluvial plains. Grow away from the coast.	blue gum	alluvial	16 c	5
12.3.11	BCF	The only RE outside of the local study area that is also classified as a primary koala habitat (AKF 2023) and therefore included in this analysis. *Eucalyptus tereticornis* +/− *Eucalyptus siderophloia, Corymbia intermedia*—open forests on alluvial plains usually near the coast.	blue gum with or without ironbark and pink bloodwood	alluvial	16 c	0

The mapping of koala habitats while also incorporating fire resilience and vulnerability is becoming increasingly necessary due to climate change and the increasing frequency and severity of wildfires [17], which may destroy koala habitats temporarily or permanently [23,24]. Knowledge of where these koala habitat areas with fire vulnerability and fire resilience are located will assist in the planning of future habitat management.

The extent and severity of fires can be mapped using remote sensing data acquired from Sentinel-2 satellites [25]. To investigate the extent of and damage to koala habitats, the spectral bands of satellite imagery can be manipulated to identify burnt areas using indices such as the Normalised Burn Ratio and calibrated with field data such as the Composite Burn Index [26]. Sentinel-2 MSI satellite data [27] are useful for analysing localised fire impacts due to their relatively high spatial (10–20 m) and temporal (5 days) resolutions [28]. By extrapolating findings from a local study area (LSA), regional assessments can be made. Regional vegetation fire studies using Sentinel-2 data have been successful worldwide [29–31]. A 230 Ha koala habitat study area [18] in SEQ was extensively burnt by a severe wildfire in mid-November 2019. Regional Ecosystem (RE) mapping (Queensland Department of Environment and Science) [32] provides information on described forest types and other vegetation types in Queensland [19] and can therefore be used in conjunction with Sentinel-2 data to expand a local fire study to a regional scale. Each Sentinel-2 scene covers about 12,000 km^2, so one scene covering a great expanse of SEQ can be classified according to the results from a local fire study, and this can in turn be applied to each of the relevant koala habitat REs.

This study identifies the distribution and extent of koala habitats in a large part of SEQ and quantifies how much of each koala habitat forest type was burnt, how badly each was burnt, and how well each one recovered. This study was conducted to identify an effective way of mapping wildfires' impacts on koala habitats and subsequent recovery at a regional scale. This study asks the following question: How do koala habitat forest types respond to different fire severities at a regional scale? The following specific questions were addressed: (a) How much of each koala habitat forest type was burnt on a regional scale, and how severely were they burnt? (b) Where are the fire-free refugia for koalas in this study area? (c) Do some koala habitat forest types take longer to recover than others in this region?

2. Methods

2.1. Local Study Area and Forest Types

The local on-ground survey area (LSA) [18] was a 230 Ha property about 10 km south-east of Crows Nest, Queensland, Australia, located within SEQ (Figure 1) and the SEQ bioregion. The LSA has several native eucalypt forest types, comprising remnant vegetation on steep hills, and several small creeks [18]. A survey of the LSA found that the types of forests, which were all eucalypt forests (Supplementary Figure S1), were generally consistent with RE classifications [19]. Koala habitat mapping is available for the Australian distribution of the koala (Koala Habitat Atlas; KHA) [14] and based on the constituent tree species of the vegetation-mapping units produced by state government authorities. It is classified according to the known tree preferences of koalas. In Queensland, the KHA is based on RE mapping [32] at 1:25,000 scale for SEQ. It includes a variety of vegetation types classified by floristics and structure, including forests, woodlands, wetlands, rainforest, etc. Three REs in SEQ have been identified as 'Primary' koala habitats by the Australian Koala Foundation [14]. Two 'Primary' Koala habitats are found in the LSA; they are mnemonically coded as GBS (mountain blue gum and stringybark on granite; RE 12.12.23) and BFA (blue gum on alluvial flats) (Table 1). There are also two REs present in the LSA classified as 'Secondary A' [12], also constituting valuable koala habitats. These are IPR (ironbark and pink bloodwood on granite ridges; RE 12.12.12) and IBM (ironbark and blue gum on microgranite; RE 12.8.16) (Table 1). The third 'Secondary A' habitat is very limited in extent and devoid of koala food trees (as defined by AKF) [12], and this RE was excluded from this study. The sixth RE present in the LSA is a wetland and was also excluded.

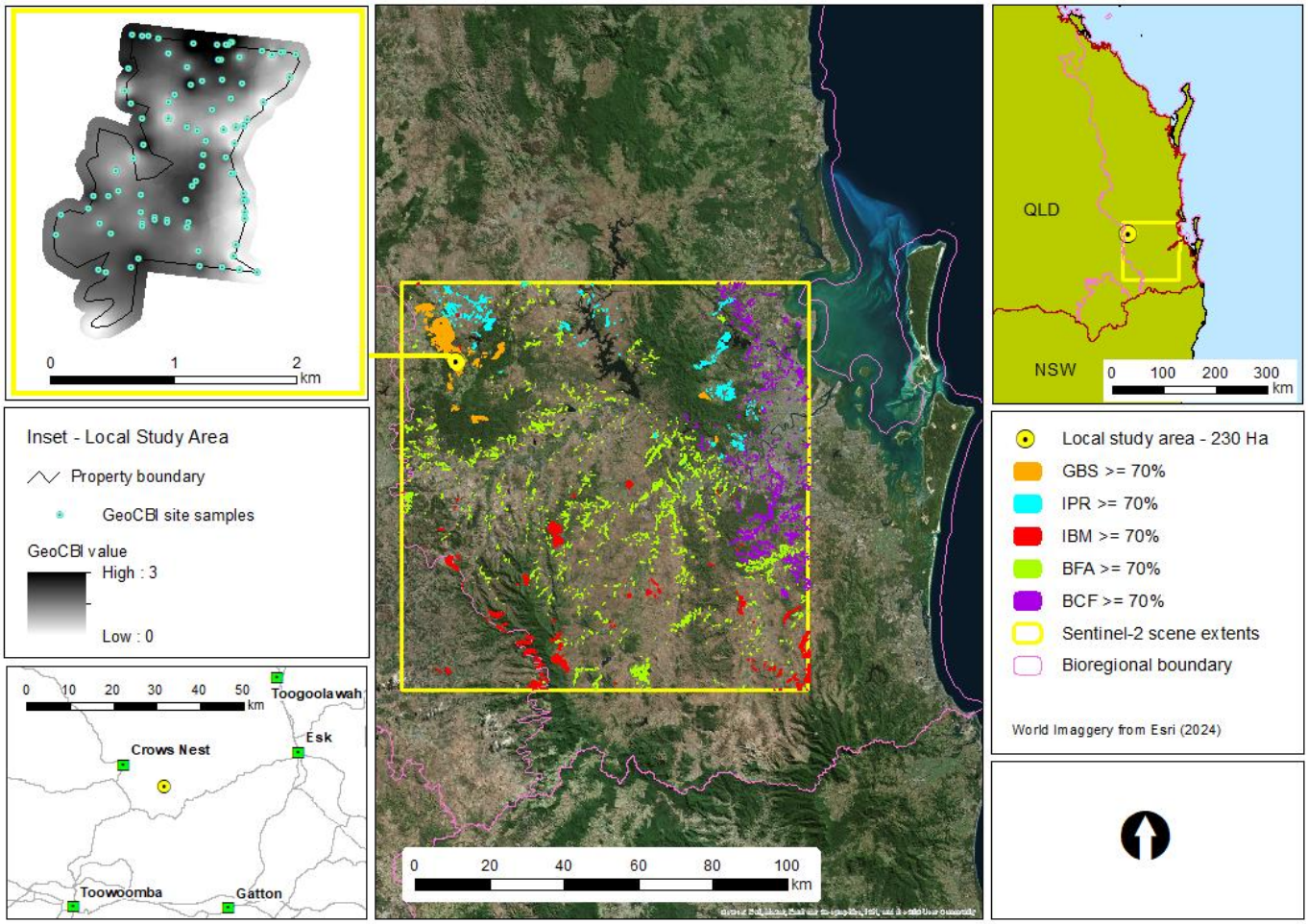


Figure 1. Map showing the regional study extent and the location of the local study area (LSA) therein (centre panel and right-hand legend and inset). The forest types comprising 70% or greater of the vegetation in an area are as follows: GBS = grey gum, mountain blue gum, and stringybark; IPR = ironbark on ridges; IBM = ironbark and mountain blue gum on microgranite; BFA = blue gum flats on alluvium inland; BCF = blue gum flats on alluvium closer to the coast. The upper left-hand panel shows the LSA with the locations of the 'Plotless sites' used to identify forest types (Regional Ecosystems) and collect the GeoCBI samples. Raw GeoCBI continuous values range from 0 to 3 and were derived from GeoCBI values from the sites, but they were reclassified in this study into classes 0–5. The lower left-hand panel shows the nearest towns and road network.

By adding the third bioregional primary koala habitat RE to this study, which was not observed within the LSA, the complete coverage of all primary koala habitats within a large part of the SEQ bioregion was achieved. This habitat was BCF (blue gum on alluvial flats closer to the coast and not within the LSA: RE 12.3.11) (Table 1). The REs in the LSA were assessed and mapped from field survey sites (Figure 1), and then the RE mapping [32] was used to investigate regional impacts for these REs. Only BCF, the RE of interest outside the LSA, lacked field data.

The LSA was assessed using 88 plotless sample sites (Figure 1) in a stratified random arrangement to include all terrain types and all fire severity and recovery types [18]. The LSA was first surveyed in early 2020 to identify the REs within it, validate and revise existing RE mapping via QDES [32], and assess fire impact severity. Revised RE mapping within the LSA was performed at a finer scale of approximately 1:5000 so that sample sites could be correctly located and classified [18].

The fire in the LSA occurred in November 2019 (late spring), and the impact survey was conducted in February 2020 (soon after in late summer). The plotless sites were

revisited annually to monitor recovery in late 2020 and then in 2021 and 2022. Fire recovery monitoring for our study was limited to three years, set as the minimum anticipated time to observe recovery but also to allow the acquisition of adequate data to yield timely research findings. It is acknowledged that further monitoring could be of additional benefit, but the results will indicate if benefits decrease beyond this time. The influence of terrain (slope and aspect) was assessed to determine the consistent impact among similar terrain classes [18]. The criteria for fire severity ratings (FSRs) [18] were assigned to a range from 0 to 5 (Table 2, Figure 2) based on post-fire observations in the LSA [18] and similar fire studies in Australia conducted by other researchers [33,34].

Table 2. Criteria for fire severity ratings (FSRs) [18].

Class	Fire Impact Severity Criterion
0	none
1	low (<2 m were scorched)
2	moderately low (2–5 m were scorched)
3	moderately high (just trunks were scorched at >5 m OR a minority of crowns were scorched)
4	high (most crowns were scorched)
5	severe (crown foliage is gone; ground is bare)

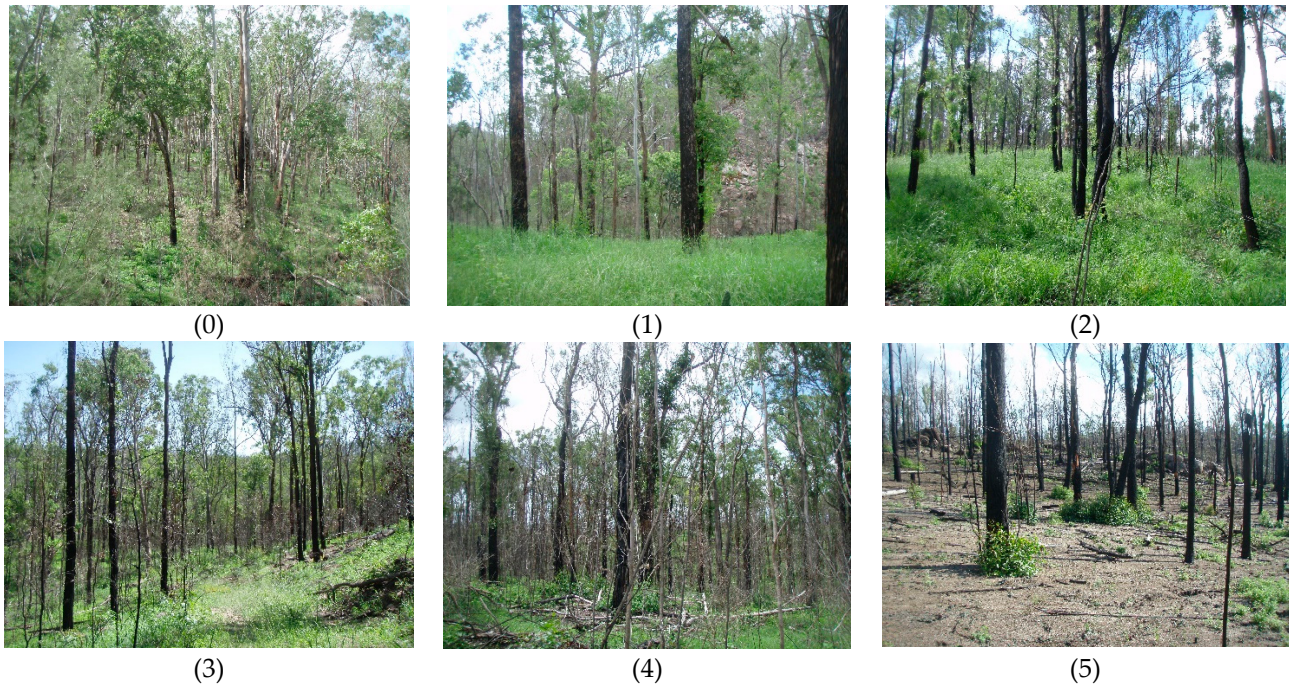


Figure 2. Typical burn severities of eucalypt forest three months after the fire in the local study area. Ratings range from 0 to 5. (0) None. (1) Low (<2 m scorch)—note recovery of the ground layer. (2) Moderate low (2–5 m scorch)—note some epicormic shooting. (3) Moderate high (just trunks scorched >5 m OR a minority of crowns scorched). (4) High (most crowns scorched)—note recovery via epicormic shooting. Also note recovery of ground layer, which may look like canopy recovery from remote sensing. (5) Severe (crown foliage gone, ground bare)—note topkill and recovery via coppicing.

A more detailed post-fire assessment was made using the GeoCBI (geometrically structured composite burn index) [25] from detailed field photographs. The GeoCBI is a modification/improvement of the Composite Burn Index [26], which is an on-ground assessment of the effect of fire on vegetation and soil and measures burn severity on each of the vegetation strata on a site. The GeoCBI adds a fraction of cover (FCOV) for each

stratum and the leaf area index (LAI) for the intermediate and tall-tree strata, and a rating is applied to each site. In our study, it was not possible to record changes in the leaf area index (LAI), as pre-burn data were not available. The use of other remote-sensing-based indices instead of GeoCBI was also considered, including the Burn Area Index (BAI) or Relativised Burn Ratio (RBR). The BAI is dependent on persistence of charcoal, whose presence is more typical in Mediterranean areas [35]. The RBR was tested in the Western United States [36], but unlike our study, the plant communities tested are not eucalypt forests, so this metric was not preferred, whereas the GeoCBI has been tested successfully in Australia with eucalypts [37]. The GeoCBI uses a straightforward set of field-collected criteria, making it suitable for calibration of remotely sensed data, but the leaf area index (LAI) needs to be measured before and after a fire, so pre-fire measurement may not have been foreseen in some instances. Goodness-of-fit of the GeoCBI with remotely sensed data can be tested using regression. Extending the use of the GeoCBI to a regional scale, based on locally collected data, may have limitations due to regional environmental variation, but this also applies to other methods such as those using the BAI and RBR. In our study, a comparison of the FSR and the GeoCBI with the dNBR using regression [38] confirmed that both methods correlated with the dNBR based on 88 plotless sample sites in the LSA. For FSR, R = 0659, and for GeoCBI, R = 0.716. GeoCBI values were accordingly categorised into six classes (0–5) similar to FSR (Table 1). Within the LSA, the GeoCBI values ranged from 0.0002 to 2.8667, with a mean value of 1.777.

2.2. Regional Context

The regional study area, including the LSA, is located in the southern part of SEQ, which forms the SEQ bioregion [20]. There are currently 172 Regional Ecosystems (REs; plant communities) recognised and mapped in this bioregion with mapping [32] and descriptions [19]. The RE mapping covers the whole of Queensland and is publicly available in digital format at 1:100,000 scale statewide and at 1:25,000 scale for the SEQ bioregion. At the national scale, RE classes are generalised into Broad Vegetation Groups at 1:1,000,000 scale [39–41], but this scale was too coarse for our study.

The five REs of interest (Table 1) were overlaid on five Sentinel-2 scenes covering a significant portion of the southern half of the SEQ bioregion. Each scene, or tile, covers an area of slightly greater than 100 km × 100 km (12,000 km^2; scenes overlap). The coverage excluded the state of NSW to the south, for which a different vegetation-mapping system is used; the Pacific Ocean to the east; and the Brigalow Belt bioregion to the west (markedly different vegetation types) [19,32]. The regional area of interest was reduced to a single Sentinel-2 scene, which included the LSA, and all five of the REs of interest (Figure 1). This area constitutes almost 20% of the SEQ bioregion, which covers approximately 66,000 km^2 [20]. The LSA is located towards the north-west corner of the Sentinel-2 scene, and adjacent scenes were not used because the Brigalow Belt bioregion is located about 20 km west, and there were a limited number of REs of interest to the north. The LSA was far away enough from the Brigalow Belt bioregion to eliminate edge effects, and the five REs of interest were well distributed across the selected Sentinel-2 scene. A map of the five Sentinel-2 scene extents, and the REs of interest in relation to these extents, is shown in Supplementary Figure S2. Within the regional area covered by the Sentinel-2 scene, RE mapping was clipped into each RE of interest by using ArcGIS v10.8 [42]. RE polygons include both single (pure, 100%) RE types and mosaics, which are mixed with other RE types as a proportion (e.g., RE type 1, 70%; RE type 2, 30%). The satellite imagery (to be processed) was considered reliable for 100% (pure) polygons but less reliable as the proportion of RE types mixed. Excluding all mosaic polygons would have significantly under-represented each RE of interest, so a minimum of 70% dominance was used [41,43,44]. This allowed up to 30% of confounding RE types to occur within mosaics, which could reduce the reliability of the dNBR but generally increase the inclusion of the RE of interest.

2.3. Data Sets and Sources

Datasets used in this study (other than field sample sites) were sourced from public web servers (Table 3). The RE mapping [32] was obtained from a geodatabase polygon file (ArcGIS v10.8) [42] with several attributes, and those used were RE and mosaic percentage of each RE (up to five REs per polygon). Field data included the GeoCBI, Fire Severity Ratings (FSRs), and the RE mapping revision (forest types), and all were stored as shapefiles (ArcGIS v10.8) [42]. Sentinel-2 MSI data [27] (Table 4) was selected for analysis due to their relatively high temporal and spatial resolutions compared to other earth observation products. These datasets were analysis-ready data from Digital Earth Australia (DEA) [45]. Optical surface reflectance data were standardised using pre-processing models already processed by DEA to correct inconsistencies in upper-atmospheric reflectance values, including aerosol optical thickness and ozone, atmospheric correction coefficients, MODTRAN, and FMASK [45]. Cloud-free images were selected. Inconsistencies in terrain were already corrected by DEA using nadir-corrected bidirectional-reflectance-distribution-function-adjusted reflectance (NBAR) with additional terrain illumination correction (NBART) [45]. The quality assurance processes are detailed by FrontierSI [46]. These corrections were applied uniformly across all temporal images for a single scene. Queensland Fire Scar Mapping [47] is a geodatabase [42] of data collected based on methods developed by Goodwin and Collett [48] and Hardtke et al. [49] (Supplementary Table S2). Fire history mapping [50] was in shapefile format [42], based on reports of fire timing (start to finish) and extent, and used to confirm which fires within the regional study area were burning in between the pre- and post-fire Sentinel-2 dates in November 2019. Regional koala records for the last 10 years were obtained from the Atlas of Living Australia [51].

Table 3. Datasets used in this study.

Dataset	Map Scale	Source	Description
Regional Ecosystem mapping	1:25,000	Queensland Herbarium, QLD Dept. Environment and Science 2023	Vegetation mapping of Queensland
Sentinel-2	20 m pixels	Geoscience Australia 2023	Analysis-ready data from Digital Earth Australia
GeoCBI sample sites	1:5000	Johnson and Shapcott, 2024	88 plotless field sites
Fire severity rating (FSR) sample sites	1:5000	Johnson and Shapcott, 2024	88 plotless field sites
Fire recovery sample sites	1:5000	Johnson and Shapcott, 2024	88 plotless field sites
Fire history mapping	1:100,000 nominal depends on source	Queensland Parks and Wildlife Service 2021	Mapping of reported fires in Queensland 1930 to 2023
Fire scar mapping	20 m pixels	Queensland Dept. Environment and Science 2023	Mapping of fires in Queensland based on dNBR 2019 to 2020

Table 4. Dates the field data were collected and Sentinel-2 scenes that were analysed.

Event	Month and Year	Best Image Date (No Clouds or Smoke)	Satellite
Pre-fire (2 years)	September 2017	7 September 2017	2B
Pre-fire (1 year)	December 2018	21 December 2018	2B
Pre-fire (10 days)	November 2019	6 November 2019	2B
Fire (not used)	November 2019	16 November 2019 (mid-burn not analysed)	2B
Fire (just after)	December 2019	6 December 2019	2B
Recovery Year 1	November 2020	20 November 2020	2B
Recovery Year 2	May 2021	14 May 2021	2A
Recovery Year 3	February 2022	18 February 2022	2A

2.4. Remote Sensing Data Analysis

The NIR and SWIR2 spectral bands from Sentinel-2 (Table 5) were used for the calculation of the Normalised Burn Ratio (NBR), the differenced NBR (dNBR), and the Normalised Difference Vegetation Index (NDVI). The imagery used was a series of scenes from 2017 through to late 2022 (used to provide years before fire), then 10 days before fire in mid-November 2019, then 20 days post-fire, and then one image per year after 2019. Sentinel-2 datasets free of clouds (with <10% cloud cover, and no clouds over the LSA) were selected to match dates of field sampling as closely as possible (Table 4). A cloud-free image taken at a date as close to before the fire as possible was selected, and the timing of images in the years preceding the fire was intended to be as close as possible to an exact year, with some variation due to cloud-free-image availability. Following the fire, a cloud-free image taken as close to immediately after the fire as possible was selected, and then recovery-year images as close to the field-work sampling dates as possible were selected (these images were cloud-free).

Table 5. Sentinel-2 band wavelengths. Bands are grouped here in order of resolution (pixel or cell size, square.) Blue, green, and red are in the visible spectrum. NIR is near infrared. Veg red edge is for vegetation. Narrow NIR is a narrower bandwidth of NIR. SWIR is shortwave infrared and divided into two bands. SWIR—cirrus detects cirrus cloud reflection. Sentinel-2A (S2A) and Sentinel-2B (S2B) orbit on opposite sides of the Earth used to halve the data collection interval, decreasing it from 10 days to 5 days.

Band Number	Resolution (m)	Name	S2A Central Wavelength (nm)	S2A Bandwidth (nm)	S2B Central Wavelength (nm)	S2B Bandwidth (nm)
2	10	blue	492.4	66	492.1	66
3	10	green	559.8	36	559.0	36
4	10	red	664.6	31	664.9	31
8	10	NIR	832.8	106	832.9	106
5	20	veg red edge	704.1	15	703.8	16
6	20	veg red edge	740.5	15	739.1	15
7	20	veg red edge	782.8	20	779.7	20
8a	20	narrow NIR	864.7	21	864.0	22
11	20	SWIR	1613.7	91	1610.4	94
12	20	SWIR	2202.4	175	2185.7	185
1	60	coastal aerosol	442.7	21	442.2	21
9	60	water vapour	945.1	20	943.2	21
10	60	SWIR—cirrus	1373.5	31	1376.9	30

Whilst vegetation recovery can be assessed with the NDVI and the Differenced NDVI (dNDVI), the dNBR was preferred for this study [52–54] to maintain consistency when comparing years of recovery to the initial fire impact, which was measured with dNBR [55]. We tested our field measurements of fire impact and recovery [18] against the Sentinel-2 data (dNBR and NDVI) in order to extrapolate our findings from the LSA (230 Ha) to a regional scale (Table 1). In our study, the NDVI was preferred over the dNDVI as it was used as a condition assessment tool, as an independent snapshot in time, and not a measurement of change. We used the dNBR to measure change.

The NDVI for each year of Sentinel-2 imagery was calculated using ArcGIS v10.8 [42]. The NDVI is a normalised ratio of near-infrared (NIR) to red:

$$NDVI = (NIR - Red)/(NIR + Red) \quad (1)$$

Sentinel-2 band for NIR = band 8a, and for Red = band 4 (Table 5). Narrow NIR from band 8a (20 m resolution) was preferred to the broader spectrum infrared from band 8 (10 m resolution). A narrower spectral resolution for NIR was considered more important for this analysis than the spatial resolution, the latter of which was adequate for a regional-scale

study. The NDVI was only used for general comparison of vegetative growth for each year, including years prior to the fire as a reference.

The differenced NBR (dNBR) calculation for each year of Sentinel-2 imagery was performed using ArcGIS v10.8 [42]. The NBR [56] is a normalised ratio of near infrared (NIR) to shortwave infrared (SWIR):

$$\text{NBR} = (\text{NIR} - \text{SWIR})/(\text{NIR} + \text{SWIR}) \quad (2)$$

The Sentinel-2 bands for NIR = band 8a, and for SWIR2 = band 12 (Table 5). Narrow NIR from band 8a (20 m resolution) was preferred to the broader-spectrum infrared from band 8 (10 m resolution). A narrower spectral resolution for NIR was considered more important for this analysis than the spatial resolution, the latter of which was adequate for a regional-scale study. This study was conducted at 20 m resolution so band 8a did not decrease overall resolution in this study. The differenced NBR (dNBR) is the difference between two NBRs calculated at different times, before and after a fire:

$$\text{dNBR} = \text{pre-fire NBR} - \text{post-fire NBR} \quad (3)$$

Resolution of the NBR was retained at 20 m, as this was sufficiently precise for regional analysis, so no resampling to 10 m resolution was necessary. This also significantly improved computation speed for repetitive analyses of entire Sentinel-2 scenes and eliminated system crashes. A resolution of 20 m is approximately equivalent to the nominal 1:25,000 scale of the base mapping of REs [32] in SEQ, where line-work precision is no finer than 25 m. The NDVI was also processed at 20 m resolution due to the regional scale of the analysis. Differentiation of small vegetation patches below 20 m resolution was not considered desirable at regional scale due to the potentially fine-scale stochastic nature of burn patterns within each patch of vegetation [57], including influence of vehicle tracks, fence lines, rocky outcrops, etc.

The dNBR was classified for fire impact and fire recovery using ArcGIS v10.8 [42]: For fire impact, the GeoCBI was used based on the 88 plotless sites in the local study area (Supplementary Figures S3 and S4). However, the GeoCBI was inadequately sensitive to differentiate very-low levels of fire severity (or relatively healthy vegetation) throughout the region. A different method of classification was therefore required to fully assess regional recovery (GeoCBI was only used for the dNBR of the year of impact, 2019). For the years of fire recovery (2020, 2021, 2022) and also impact (2019) for comparison, a system of manual breaks of the dNBR was used (Table 6). The dNBR, GeoCBI, and FSR data were explored to determine their distribution, and various categorisation methods were investigated. Finally, to draw a comparison of dNBR with GeoCBI and FSR on a temporal scale (corresponding to the year of the 2019 fire and then three subsequent years of recovery), we categorised the dNBR into 22 incremental classes (manual breaks; ArcGIS v10.8) [42] (Table 6). This was defined as a Comparable Incremental Scale Reference (CISR). Other methods of classification included in ArcGIS v10.8 [42], which were not suitable, included natural breaks (Jenks), equal interval, quantile, geometric interval, and standard deviation (ArcGIS v10.8, Supplementary Figure S5) [42]. They were unsuitable for three reasons: Firstly, the classes created did not have a common break point between years, based on an dNBR of zero, so years could not be directly compared. Scales of dNBR would also have been different, so high dNBR percentiles from one year might not be the same as high dNBR percentiles in another year. Secondly, all of those automatic classifications were unsupervised, so none of the classes could be assigned meaningful fire severities or recovery statuses (whereas GeoCBI can). Therefore, multi-temporal comparison of categories was performed based on CISR, as opposed to the use of GeoCBI for the fire impact alone. The GeoCBI intervals were different to those of the CISR, but its six FSR classes (0–5) could be aligned with those increments (Supplementary Table S3). This therefore provided some impact description to the burnt section of the CISR. Thirdly, although some of the other methods (natural breaks, quantile and standard deviation) could be used to divide the

distribution of dNBR values into meaningful classes for the year of the fire (2019), those break values could not be meaningfully transferred to later years of recovery (2020, 2021, 2022) because the distribution of dNBR values in most cases moved outside the bounds of the classes set for 2019 (note the graphical stepwise explanation in Supplementary Figure S6). Other methods were also considered, such as k-means clustering and machine learning-based approaches, but the CISR method produced the most easily interpretable and intuitive graphical results and was able to be processed within ArcGIS v10.8 [42], along with all other data in our study.

Table 6. Classification scale for dNBR for use with Comparable Incremental Scale Reference (CISR). Class 1 is a conglomerated class including several unburnt classes. Classes 11 and 12 are central classes indicative of neutral conditions (not burnt, not recovering). Class 22 is a conglomerated class including several severely burnt classes. The dNBR value immediately post-burn will show areas with no change (unburnt or non-vegetated) and high values for burnt areas. The dNBR for subsequent years provides an estimate of vegetation recovery when compared with immediate post-burn dNBR.

Class	dNBR Central Value	Burn Severity	Class	dNBR Central Value	Burn Severity
1	≤ -1	Vigorous growth	12	0.1	Neutral or minimal change
2	−0.9		13	0.2	Slightly burnt
3	−0.8		14	0.3	
4	−0.7		15	0.4	
5	−0.6		16	0.5	
6	−0.5		17	0.6	
7	−0.4		18	0.7	
8	−0.3		19	0.8	
9	−0.2		20	0.9	
10	−0.1	Slight recovery	21	1	
11	0	Neutral or minimal change	22	>1	Severely burnt

False positives from the dNBR were not a problem in this study because the RE mapping of koala habitat forest types was unlikely to contain significant wet areas such as wetlands or water bodies. The main source of false positives was agricultural areas due to changes in cropping between pre-fire and post-fire Sentinel-2 images, which generated a non-zero dNBR value. For example, a harvested crop paddock would generate a positive value, and this was observed abundantly in the Lockyer Valley, an extensive agricultural area between Toowoomba and Brisbane (Supplementary Figure S7). An agricultural mask [58] coincided with most, or possibly all, of these false positives. Nevertheless, the mapped REs of interest do not coincide with agricultural or cultivated areas.

2.5. GeoCBI Classification

The GeoCBI [25] was assigned to each of the 88 plotless sites within the LSA and then classified to enable comparison of different burn severities for each forest type. The existing classification tool from the field proforma [25] is a Burn Severity Scale ranging from 0 to 3, but it has seven sub-classes within it. In order to make this scale compatible with previous research in this LSA conducted by Johnson and Shapcott [18] (for which a Fire Severity Rating was used; Table 2), two of the intermediate sub-classes were combined to form a 0–5 scale with generalised descriptors: 0 = none, 1 = low, 2 = moderate low, 3 = moderate high, 4 = high, and 5 = severe. This GeoCBI could then be applied regionally to the dNBR.

2.6. Data Validation

A digital elevation model [59] was used to test for terrain as a confounding factor for this study by comparing dNBR values from the Sentinel-2 data with elevation, slope, and aspect values (terrain) using ArcGIS v10.8 [42] and linear regression with SPSS [38].

Weather conditions in the weeks leading up to the fire in mid-November 2019 and for the remainder of that month were consistently dry, with minimal rainfall [10,18]. Regional Ecosystem mapping (QDES 2023a) was ground-truthed in key regional locations for each RE that occurred within the LSA. In some areas that could not be visited, Google Maps Street View [60] was used. Within the LSA, GeoCBI classes from the 88 plotless sites correlated with the dNBR, with a Pearson value of 0.716 (*c.f.* [37,61]). The GeoCBI-classified dNBR was therefore accepted as a reliable indicator of wildfire severity for this study [61]. Results of burnt area mapping and total burnt areas were compared with Queensland Fire Scar Mapping [47].

2.7. Analysis

2.7.1. How Much of Each Koala Habitat Forest Type Was Burnt on a Regional Scale, and How Severely Was Each Type Burnt?

Fire impact was assessed by comparing the areas of fire severity classes (GeoCBI) within each RE. Total area calculations were obtained from raster analysis (ArcGIS v10.8) [42]. Total areas of each fire severity for each RE were also converted to percentages. These results provided information on how many koala habitats were affected by fire and how severe the impact was.

We compared total areas of each fire severity (GeoCBI classes 0–5) within each RE using the Kruskal–Wallis test in SPSS [38]. We also compared the highest fire severity (GeoCBI classes 4 and 5 combined) between REs. No statistical comparison was needed for subsequent years (of recovery) using the 2019 GeoCBI because it was not able to differentiate between areas of low fire severity at the regional scale.

2.7.2. Where Are the Fire-Free Refugia for Koalas in This Study Area?

Koala habitat areas suitable for refuge from fire were identified using the following criteria: (1) the definition of koala habitat forest type as specified in our study (i.e., REs were GBS, IPR, IBM, BFA, and BCF); (2) fire severity class 0 = unburnt; (3) proximity to burnt areas of moderate, high, and severe ratings—classes 2, 3, 4, and 5; (4) proximity to recorded koala sightings. Only koala habitat forest type areas with a koala sighting recorded less than 10 years ago were included to increase the likelihood of a koala being present in these mapped forest types.

Buffers around burnt areas ranged from being directly contiguous with the burnt area to a maximum distance equivalent to the average area of a koala's maximum home range. This was initially set at a buffer of 700 m based on mean home-range area of 39.5 Ha [62] in the event of a koala relocating to the refuge permanently or for the long term. However, home ranges were not necessarily round; they could be elongated [63] to suit resources. The distance (length) was therefore increased to 4 km (corresponding to a rectangle with a width of 100 m), which is within known travel distances of koalas [62]. This area could represent a gully, for example. All koala sighting records were buffered by the average radius of this home range area and therefore set to 350 m. The distances selected were intended to be practical minima and could be extended for various reasons, such as connectivity, or locally reduced for reasons such as land-use tenure or drought. Polygons of each criterion were buffered and then converted to raster in ArcGIS v10.8 [42]. All unburnt (fire severity class 0) areas that were overlapped by burnt area buffer were selected as refuges, provided that at least some koala sighting buffer area overlapped with the burnt area buffer.

2.7.3. Do Some Koala Habitat Forest Types Take Longer to Recover than Others in This Region?

Fire impacts based on the classified GeoCBI from the LSA were initially intended to also be used as the reference for fire recovery across the regional study area, but we found that it was not an effective regional metric when based on data from the LSA, which was relatively severely burnt. The proportional amounts of fire impact at different levels of severity in the year of the fire (2019) in the region were easily distinguished, but the subsequent years of recovery (2020, 2021, 2022) showed that almost all of the region had

suffered no fire impact or had completely recovered or was in a state of healthy growth (Table 6). This finding was similar to Queensland Fire Scar Mapping [47] and indicated that a different scaling of fire impact and recovery (CISR, based on the dNBR) needed to be developed for regional study of fire recovery to account for where fires were minimal or absent. We calculated the total areas of each fire severity level within each forest type (RE) and the total percentages of each forest type using ArcGIS v10.8 [42]. The classified dNBR data were analysed with the Bivariate Correlation package in SPSS v28.0.1.1 [38]. We used Spearman's rank correlation to test between slower and faster recovery.

As an overall assessment of original pre-fire condition for all vegetation and the impact of fire, followed by overall recovery, the NDVI was calculated for two years prior to the fire in 2019, then for 2019, and then for three years after the fire, across 88 plotless sites in the LSA [18]. This gave us a baseline from which to determine if vegetation had apparently returned to its original condition after the fire.

2.7.4. Reliability Assessment of the dNBR and NDVI for Forest Fire Recovery

Reliability of the dNBR for forest fire recovery was tested post hoc because the dNBR is a well-recognised method of assessing fire impact [54,55]. The dNBR was preferred over the NDVI for this, although both methods are suitable for monitoring recovery [64]. There are various ways of improving the reliability of the NBR (and hence the dNBR), such as reducing false positives from water bodies and clouds [65], but distinguishing between different types of vegetative growth (e.g., epicormic shooting and coppicing) may be more difficult [66]. In the case regarding vegetation recovering from fire, the dNBR can quantify overall vegetative recovery [52,53]. There are other indices for burned-area mapping, but their evaluation requires more detailed field data. For example, the Burned Area Index for Sentinel-2 (BAIS2) [67] requires leaf area index data, which we could not record in our study. Our study focusses on koala habitats and therefore requires the assessment of specific types of tree regrowth responses, namely, epicormic shooting, coppicing, and apparent tree mortality. These responses were recorded at 88 plotless sites within the LSA over three years [18] as a percentage of trees and then compared using the dNBR and the NDVI to see if these responses could be identified and quantified using regression in SPSS [38].

3. Results

3.1. How Much of Each Koala Habitat Forest Type Was Burnt on a Regional Scale, and How Severe Was the Burning?

The total burnt area of the five koala habitat REs studied in the regional area, including fire severity classes, 1–5, was 2400 Ha (Table 7), which is 10% of the total area of these REs (wherein those REs occupy >70% of the forest). Some additional area would have been burnt in REs comprising less than 70%, but this is likely to have been relatively minimal due to the sparsity of such regions. The five koala habitat REs only occupied 2% of the area of this region. The remainder of the study area was composed of other REs of probably less habitat value for koalas, non-remnant (cleared) areas, and water bodies.

The areas of each koala habitat forest type in the regional study area ranged from approximately 3000 Ha to 7000 Ha (Table 7), with GBS corresponding to 5744 Ha (mid-range), but it had approximately 10 times more area that was severely burnt in 2019 (class 5; 566 Ha; Table 8; Figure 3) than the other forest types combined (54.7 Ha). It also had almost four times more area badly burnt in 2019 (class 4; 332 Ha) than the other forest types combined (89 Ha). The fire impacts on koala habitat forest types in 2019 in the regional study area were greatest for the forest type (RE) GBS, followed by the REs IBM and IPR (Table 7; Table 1; Figure 3). There was 2910 Ha of IPR within the regional study area, of which 161 Ha was burnt, and there was 5848 Ha of IBM within the regional study area, of which 374 Ha was burnt. In contrast, for the alluvial areas, there was 6759 Ha of BFA within the regional study area, of which only 11 Ha was burnt, and there was 3199 Ha of BCF within the regional study area, of which only 1 Ha was burnt. For GBS, at least 15%

(898 Ha) experienced high-to-severe fire impacts (Table 8), with approximately 30% of the areas of GBS burnt to some degree (1855 Ha). All other REs studied (IPR, IBM, BFA, and BCF) were burnt less (only 7% burnt combined, totalling 550 Ha) and suffered a minimal impact from high-to-severe fire intensities (3%, 140 Ha). The overall impacts on the two alluvial REs BFA and BCF were negligible. In subsequent years (2020, 2021, 2022), almost nothing was classified as burnt or unrecovered based on the GeoCBI (Table 8, Figure 3).

Table 7. Summary of areas burnt within each forest type (Regional Ecosystem (RE)) within the regional study area (with an area of approximately 12,000 km^2) in 2019. Burnt areas are classes 1–5 and exclude class 0, unburnt. Forest types: GBS = grey gum and mountain blue gum and stringybark (RE 12.12.23); IPR = ironbark on ridges (RE 12.12.12); IBM = ironbark and mountain blue gum on microgranite (RE 12.8.16); BFA = blue gum flats on alluvium inland (RE 12.3.3); BCF = blue gum flats on alluvium closer to the coast (RE 12.3.11). The REs studied were restricted to those mapped areas [32] of greater than 70% of a particular RE due to the limitations of the dNBR in detecting small proportions of the RE (when mixed with other REs).

Forest Type	GBS	IPR	IBM	BFA	BCF	Total
RE	12.12.23	12.12.12	12.8.16	12.3.3	12.3.11	
Total area in bioregion Ha ˆ	15,000	53,000	33,000	38,000	40,000	179,000
Total study area of RE > 70% *	5744	2910	5848	6769	3199	24,470
Proportion within bioregion %	38.0	5.5	17.7	17.8	8.0	13.7
Burnt study area Ha *	1855	161	374	11	1	2402
Burnt study area % *	32.3	5.5	6.4	0.1	0.03	9.8

ˆ Total area of all of the REs in the whole bioregion (QDES 2023b), including smaller percentages of mapped patches of remnant vegetation (from 100% to as little as 5% of the patches). * Based on REs constituting 70% or greater of a mapped patch of remnant vegetation within the regional study area covered by one Sentinel-2 scene (approximately 12,000 km^2).

Table 8. Regional fire severity impact with classes based on the GeoCBI from the local study area for the year of the fire, 2019, and those same classes applied to recovery in the following years. The regional study area defined by the Sentinel-2 scene is 1,2056.04 km^2. Forest types: GBS = grey gum, mountain blue gum, and stringybark (RE 12.12.23); IPR = ironbark on ridges (RE 12.12.12); IBM = ironbark and mountain blue gum on microgranite (RE 12.8.16); BFA = blue gum flats on alluvium inland (RE 12.3.3); BCF = blue gum flats on alluvium closer to the coast (RE 12.3.11). GeoCBI burn classes: 0 = none, 1 = low, 2 = moderate low, 3 = moderate high, 4 = high, and 5 = severe. Total areas for each RE were subject to minor variation in later years. Values are rounded.

Total Ha All GeoCBI Classes	**5744**	**2910**	**5848**	**6769**	**3199**	**24,470**
2019						
GeoCBI class	GBS Ha	IPR Ha	IBM Ha	BFA Ha	BCF Ha	Total Ha
0	3889	2749	5473	6759	3198	22,069
1	377	66	120	2	1	566
2	321	39	86	1	0	448
3	259	23	62	1	0	345
4	332	22	64	2	0	421
5	566	10	41	4	0	621
Total burnt area in Ha (classes 1–5)	1855	161	374	11	1	2402
2020						
GeoCBI class	GBS Ha	IPR Ha	IBM Ha	BFA Ha	BCF Ha	Total Ha
0	5744	2909	5850	6769	3178	24,451
1	0	0	0	0	9	9
2	0	0	0	0	5	5
3	0	0	0	0	5	5
4	0	0	0	0	3	3
5	0	0	0	0	0	0
Total burnt area in Ha (classes 1–5)	0	0	0	0	21	21

Table 8. *Cont.*

Total Ha All GeoCBI Classes	**5744**	**2910**	**5848**	**6769**	**3199**	**24,470**
2021						
GeoCBI class	GBS Ha	IPR Ha	IBM Ha	BFA Ha	BCF Ha	Total Ha
0	5744	2910	5850	6769	3198	24,472
1	0	0	0	0	0	0
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	0	0	0	0	0	0
5	0	0	0	0	0	0
Total burnt area in Ha (classes 1–5)	0	0	0	0	0	0
2022						
GeoCBI class	GBS Ha	IPR Ha	IBM Ha	BFA Ha	BCF Ha	Total Ha
0	5651	2908	5849	6761	3193	24,362
1	28	1	0	4	1	34
2	24	1	0	1	1	27
3	19	1	0	1	1	21
4	19	1	0	2	1	22
5	3	0	1	2	1	8
Total burnt area in Ha (classes 1–5)	93	2	1	11	5	113



Figure 3. Regional fire severity percentages of total area for each forest type tested (GBS, IPR, IBM, BFA, BCF) for 2019, the year of the fire. The regional study area defined by the Sentinel-2 scene is

12,056.04 km^2. Forest types: GBS = grey gum, mountain blue gum, and stringybark (RE 12.12.23); IPR = ironbark on ridges (RE 12.12.12); IBM = ironbark and mountain blue gum on microgranite (RE 12.8.16); BFA = blue gum flats on alluvium inland (RE 12.3.3); BCF = blue gum flats on alluvium closer to the coast (RE 12.3.11). GeoCBI burn classes: 0 = none, 1 = low, 2 = moderate low, 3 = moderate high, 4 = high, and 5 = severe.

3.2. Where Are the Fire-Free Refugia for Koalas in This Study Area?

The fire-free refugia for koalas in the regional study area were found to be widespread, with the largest areas being situated around the LSA near Crows Nest (Regional: Figure 4; Inset: Figure 5) and on the Main Range, a mountain range between Allora and Boonah. There were several smaller areas throughout the region based on smaller fires identified.

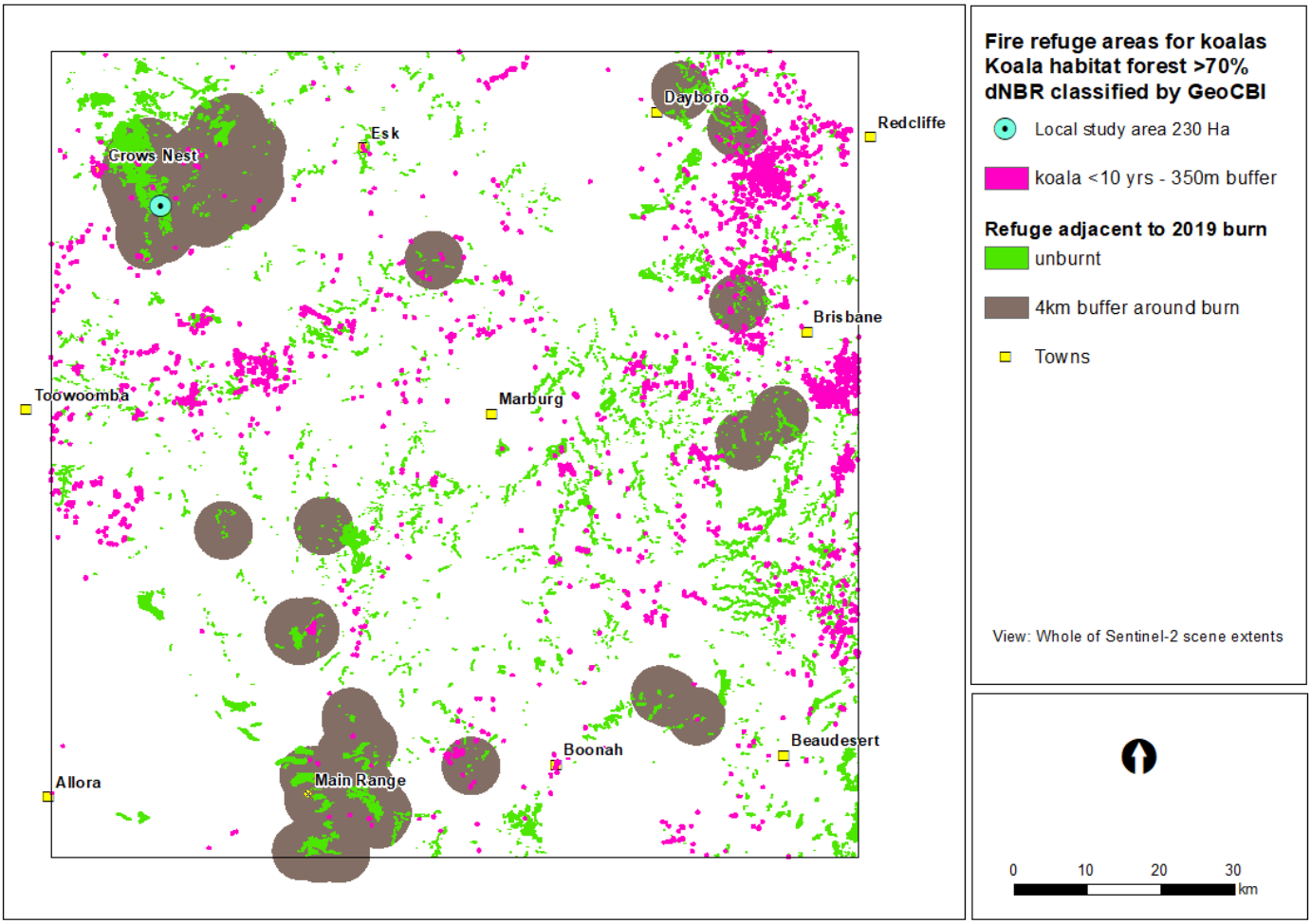


Figure 4. Koala habitat areas suitable for refuge from fire. View covers the entire Sentinel-2 scene. Criteria are (1) koala habitat forest type; (2) fire severity class 0—unburnt; (3) proximity to burnt areas with moderate, high, and severe ratings—classes 2, 3, 4, and 5; and (4) proximity to recorded koala sightings.

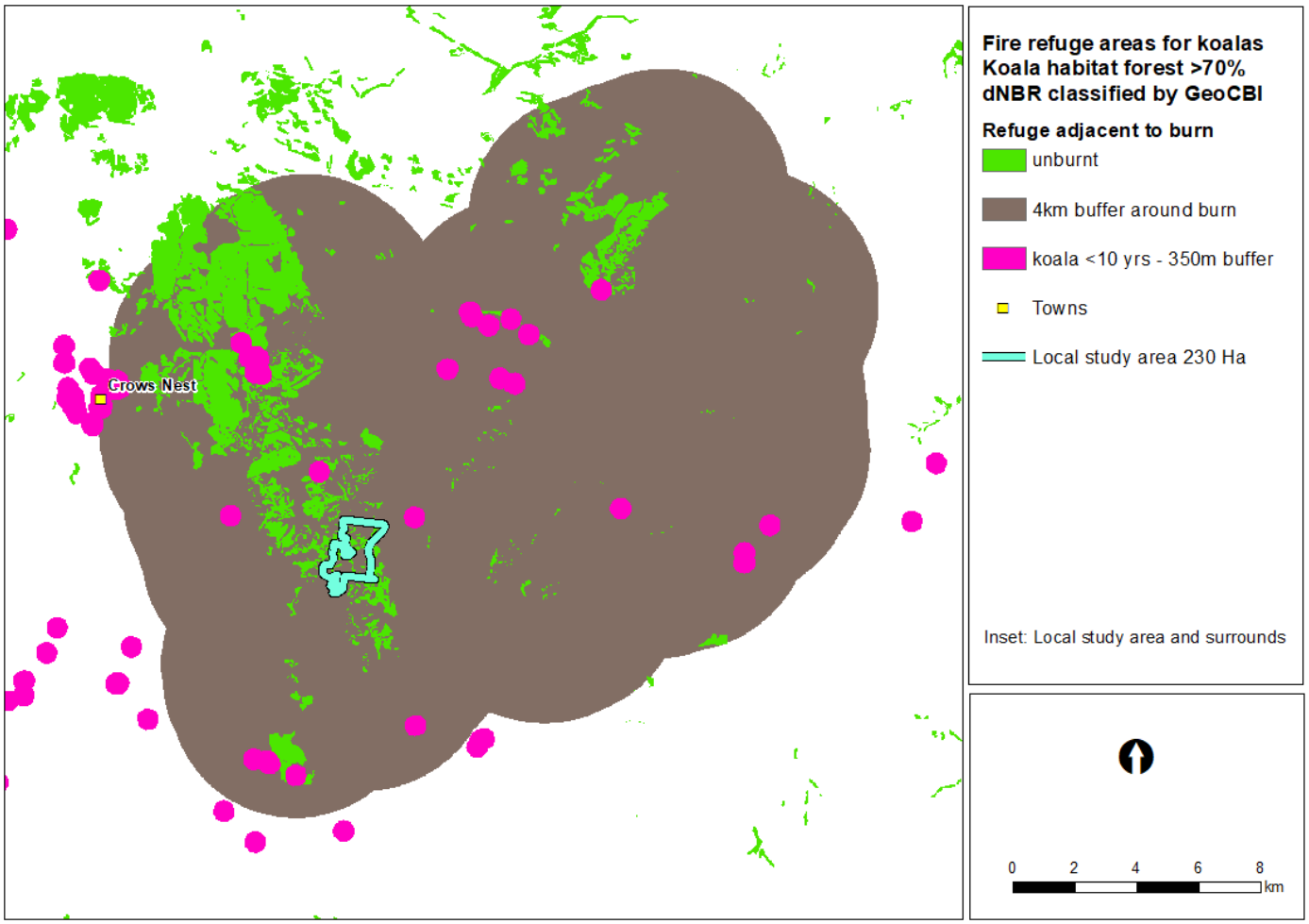


Figure 5. Koala habitat areas suitable for refuge from fire. View is local study area and its surrounds. Criteria are (1) koala habitat forest type; (2) fire severity class 0—unburnt; (3) proximity to burnt areas with moderate, high, and severe ratings—classes 2, 3, 4, and 5; and (4) proximity to recorded koala sightings.

3.3. General Recovery Trend

The NDVI measurements indicated that vegetation cover returned to previous extents during the recovery phase after the fires (Figure 6). A significant drop in NDVI values in 2019 was confirmed ($p < 0.001$, Kruskal–Wallis H = 330.277).

The mean dNBR values for each forest type studied were all positive (>0) in the year of the fire (2019) and then in all cases became increasingly negative in progressive years of recovery (2020, 2021, 2022; Figure 7). The results for all the forest types are similar, except for GBS, which experienced the greatest fire impact (dNBR > 0.2), and BCF, which showed the least apparent recovery from fire, with dNBR values for each recovery year of about −0.3, whereas the other forest types showed dNBR values of about −0.4.

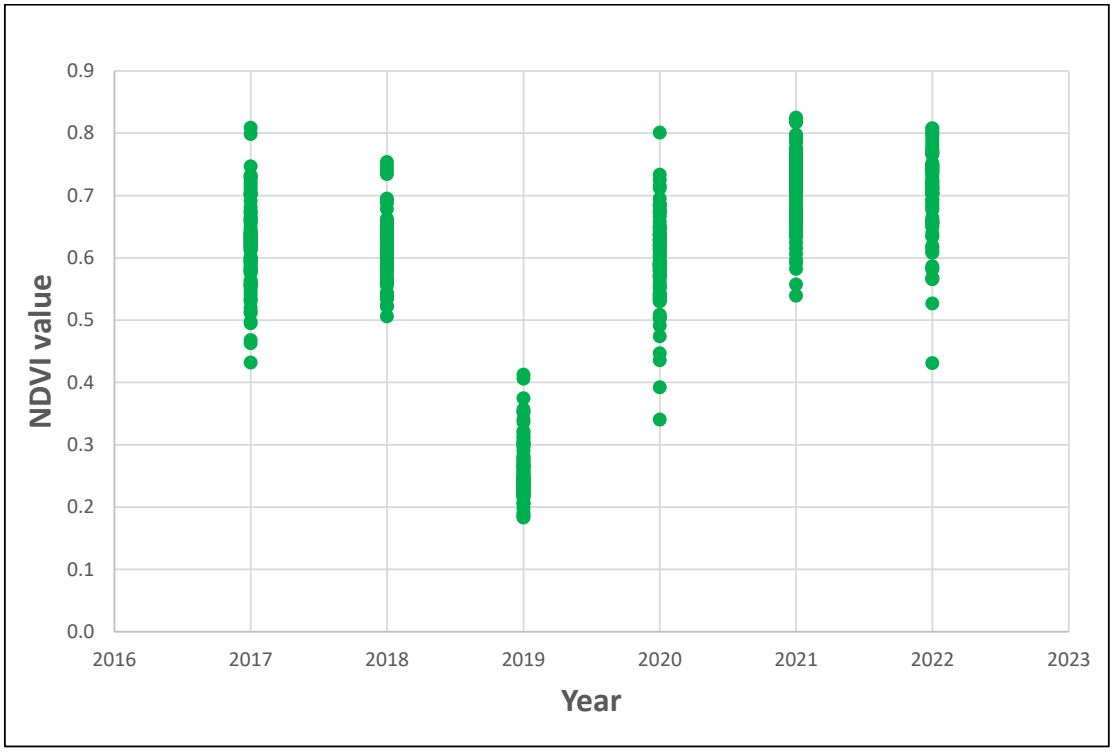


Figure 6. Normalised Difference Vegetation Index (NDVI) measured for two years prior to the fire in 2019, and three years after the fire, across 88 plotless sites in the local study area.

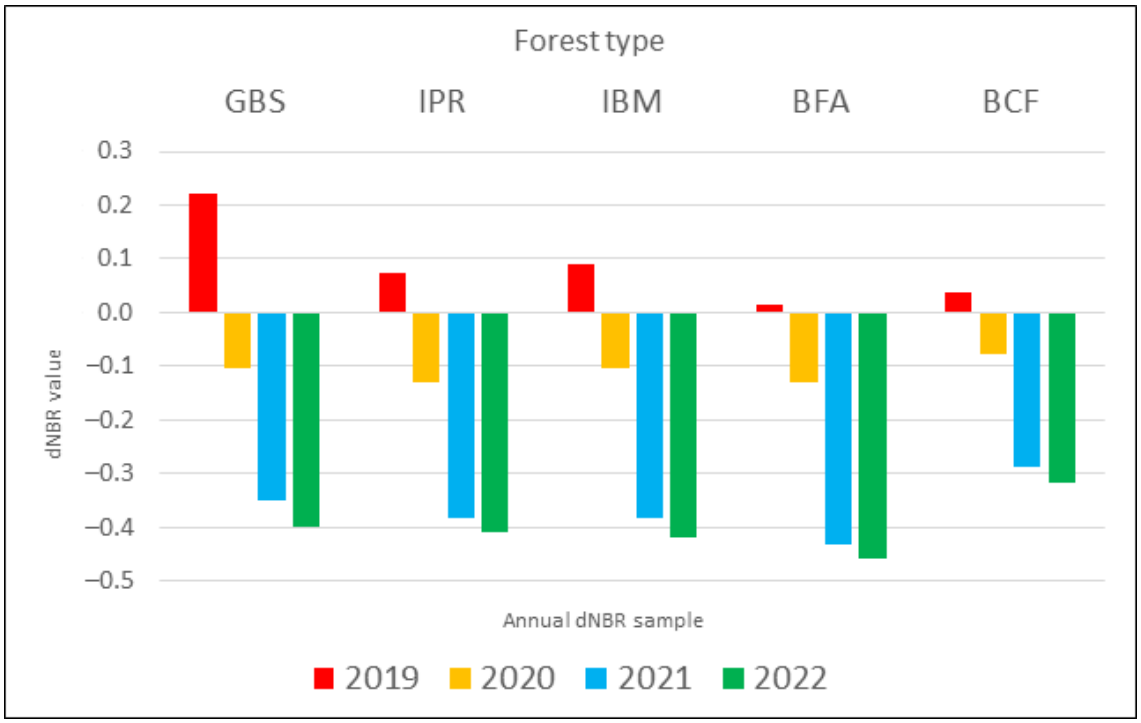


Figure 7. Mean dNBR values for each forest type in each year. A negative dNBR indicates no burning, a dNBR of 0 is neutral (with no change between two years), and a dNBR >= 1 in this study indicates severe burning. Forest types: GBS = grey gum, mountain blue gum, and stringybark (RE 12.12.23); IPR = ironbark on ridges (RE 12.12.12); IBM = ironbark and mountain blue gum on microgranite (RE 12.8.16); BFA = blue gum flats on alluvium inland (RE 12.3.3); BCF = blue gum flats on alluvium closer to the coast (RE 12.3.11).

3.4. Do Some Koala Habitat Forest Types Take Longer to Recover than Others in This Region?

The distribution of areas across the 0.1 dNBR increments of fire severity (Figure 8) shows modes (highest scores) for each RE, and in 2019, they mostly have a slightly positive dNBR value (zero is neutral; Table 6). Although GBS has the lowest mode (see Supplementary Tables S4–S7 of results that support the graphical figures), it is bimodal and has a second peak at class 15, which is a higher fire severity.

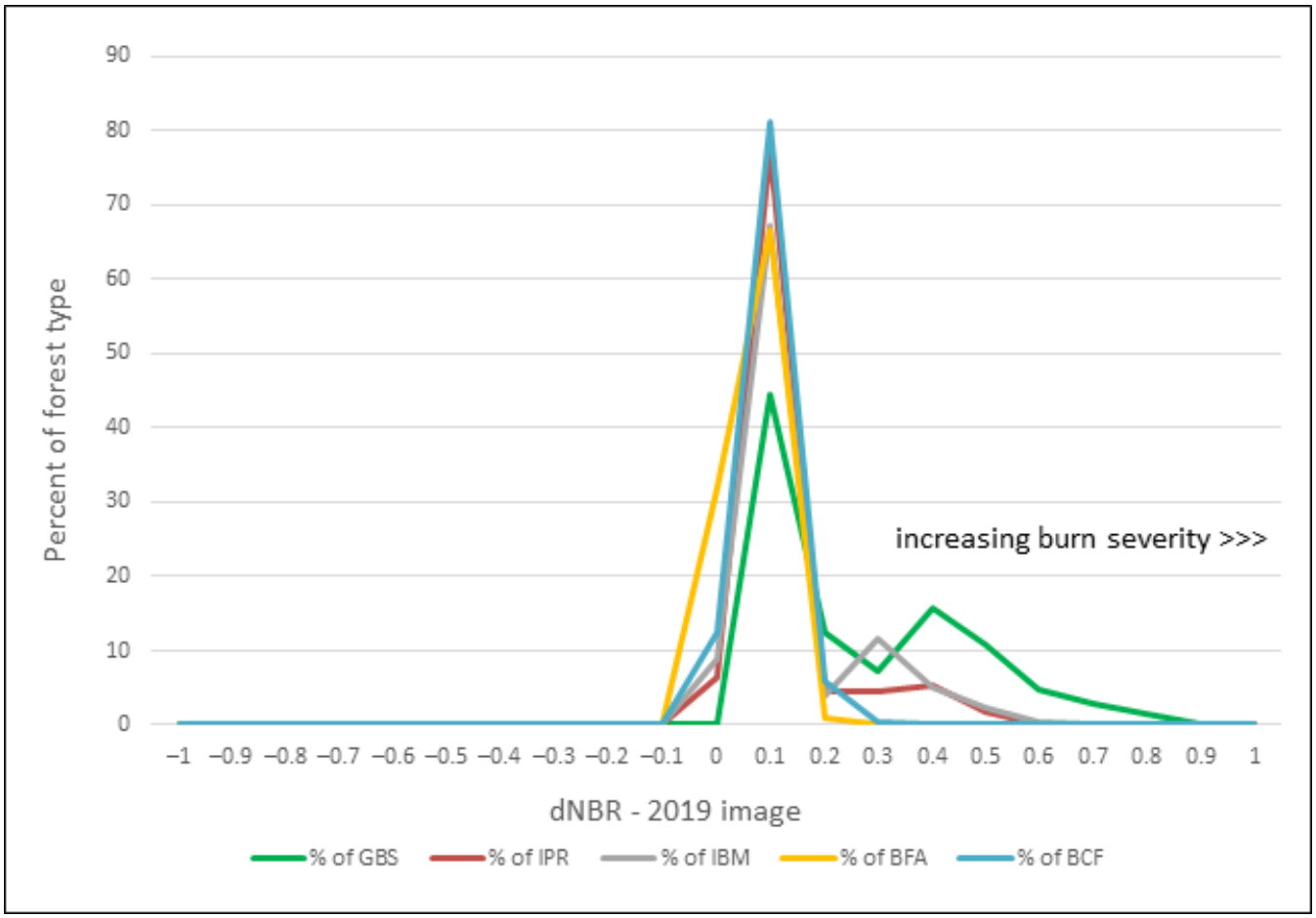


Figure 8. Burn severity classes for koala habitat forest types (Regional Ecosystems) at the regional scale across one whole Sentinel-2 scene (covering an area of 100 km × 100 km) in 2019, immediately after the fire. Negative dNBR indicates unburnt, a dNBR of 0 means neutral (with no change between two years), and dNBR ≥ 1 in this study indicates severely burnt. Forest types: GBS = grey gum, mountain blue gum, and stringybark (RE 12.12.23); IPR = ironbark on ridges (RE 12.12.12); IBM = ironbark and mountain blue gum on microgranite (RE 12.8.16); BFA = blue gum flats on alluvium inland (RE 12.3.3); BCF = blue gum flats on alluvium closer to the coast (RE 12.3.11).

In contrast to the year in which the fire had an impact, i.e., 2019, for the first year of recovery (2020) and both subsequent years, all REs were found to have a unimodal distribution of growth response (Figure 9, Supplementary Figures S8 and S9). All REs showed a slightly negative peak response (zero is neutral; Table 6), indicating most areas were not burnt.

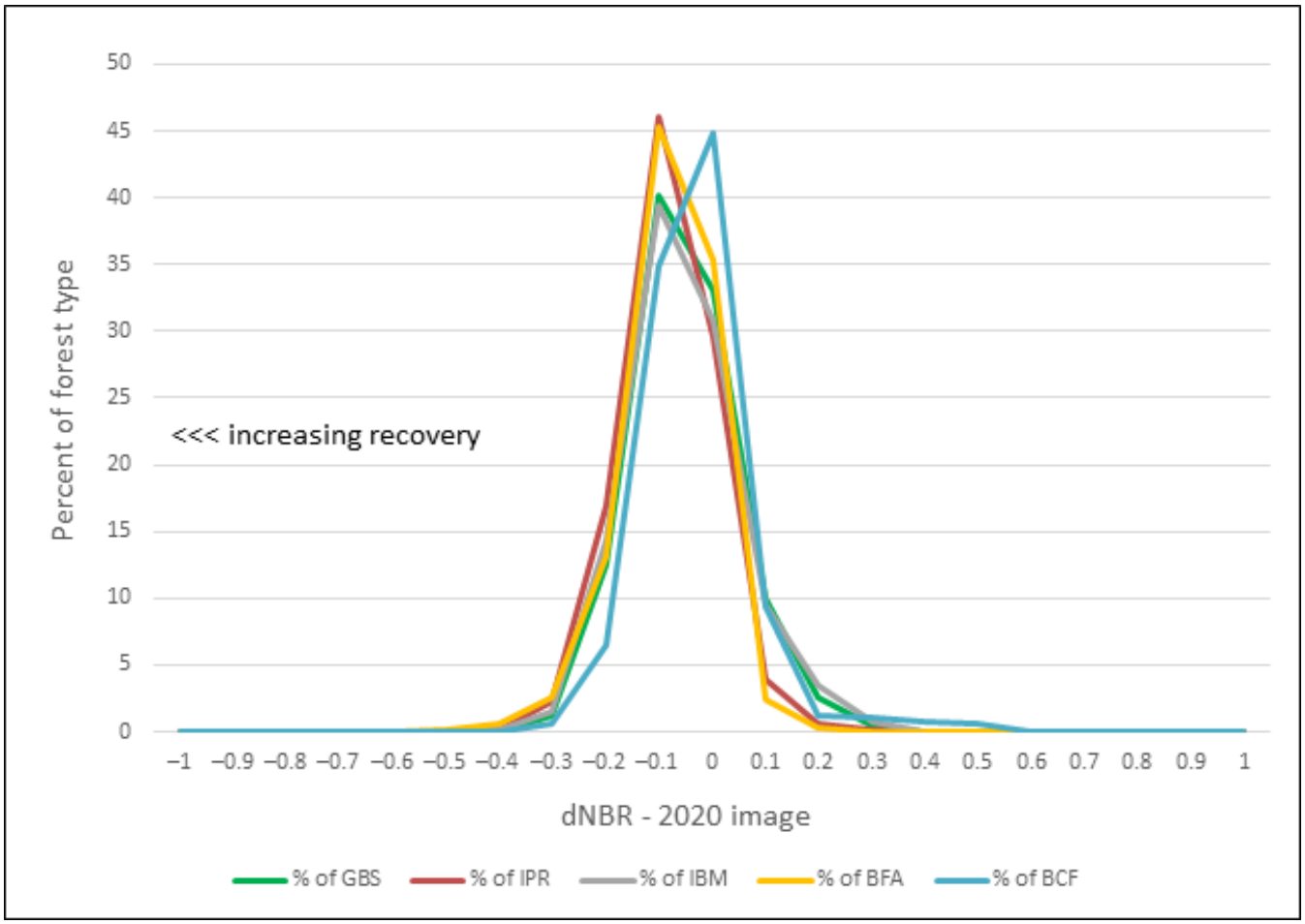


Figure 9. Burn severity classes for koala habitat forest types (Regional Ecosystems) at the regional scale across one whole Sentinel-2 scene (an area of 100 km × 100 km) in 2020, one year after the fire. Negative dNBR indicates unburnt, an dNBR of 0 means neutral (with no change between two years), and dNBR ≥ 1 in this study indicates severely burnt. Forest types: GBS = grey gum, mountain blue gum, and stringybark (RE 12.12.23); IPR = ironbark on ridges (RE 12.12.12); IBM = ironbark and mountain blue gum on microgranite (RE 12.8.16); BFA = blue gum flats on alluvium inland (RE 12.3.3); BCF = blue gum flats on alluvium closer to the coast (RE 12.3.11).

A comparison was also made of the yearly changes in the total areas for each 0.1 increment in dNBR (CISR) for each forest type (RE) across the regional study area (Figure 10). For all the REs studied, the values and peak values of dNBR were highest in the year of the fire (2019) and became progressively lower in the subsequent years of recovery. The forest type GBS was the only RE studied that had a bimodal distribution of high fire severity, with a higher fire severity impact overall. All forest-type REs then experienced a reduction in their dNBR values in the first year of recovery (2020; e.g., IPR, Figure 10) and then a further reduction in dNBR in the second and third years (2021 and 2022). For all forest types studied, there was no further reduction in dNBR values from 2021 to 2022, indicating that minimal change occurred from 2021 to 2022 (Supplementary Figures S10–S12). This correlation of dNBR distributions between 2021 and 2022 was confirmed to be highly significant ($p < 0.001$), with Spearman values of $r_s = 0.953$ for GBS, $r_s = 0.948$ for IPR, $r_s = 0.969$ for IBM, $r_s = 0.967$ for BFA, and $r_s = 0.976$ for BCF. All other r_s values were less than 0.9, and, in most cases, they were less than 0.8, indicating that the dNBR values were similar between other years but not as closely correlated as between 2021 and 2022.

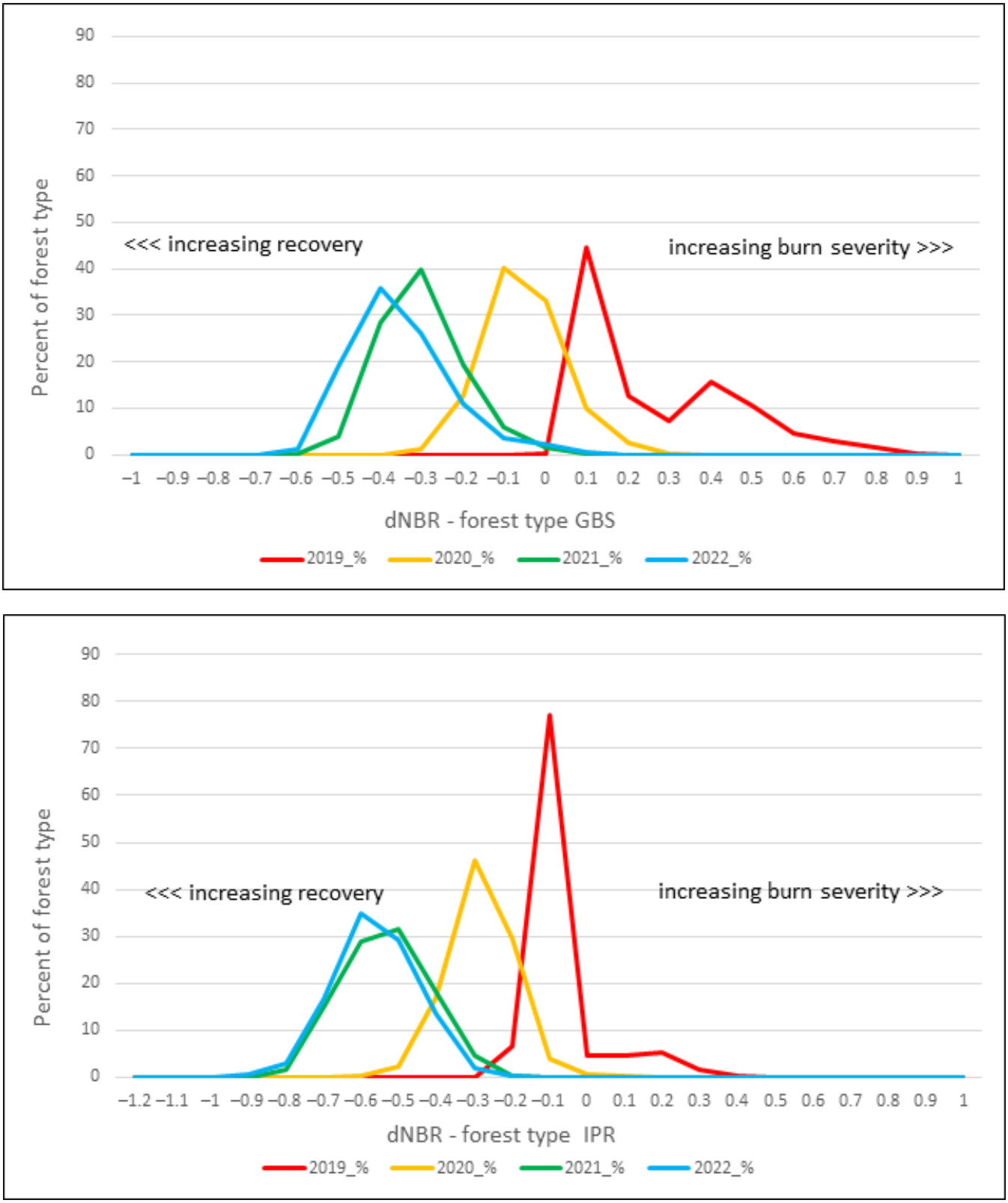


Figure 10. Burn severity and recovery trend for forest type GBS (RE 12.12.23) and forest type IPR (RE 12.12.12) in the study region. Colour coding: red indicates year of fire, and other colours are years of recovery. Negative dNBR indicates unburnt, an dNBR of 0 means neutral (with no change between two years), and dNBR ≥ 1 in this study indicates severely burnt.

Queensland Fire Scar Mapping [47] (Supplementary Figure S13) did not differentiate between forest types (REs) or fire severities, but within our study area, it had similar overall indications of recovery (Figure 10), with approximately 4% of the regional study area (clipped to the same Sentinel-2 scene) being burnt in 2019 and less than 1% being burnt in the following years, i.e., 2020 and 2021. These were new fires and not an indication of recovery from previous fires.

3.5. Reliability Assessment of the dNBR and NDVI for Forest Fire Recovery

Tree recovery responses, namely, epicormic shooting, coppicing, and apparent tree mortality, did not correlate with the dNBR values for each of the three years of recovery (Figure 11). The dNBR values were highest in 2020, the year immediately after the fire, and then reduced in subsequent years. However, high values of field-observed tree responses (in this case, epicormic shooting) did not correlate with low dNBR values. A linear regression found no correlation between the two variables, A similar recovery response was recorded for coppicing and for trees with no signs of life, with similar non-significant regression results (Supplementary Figures S14 and S15).

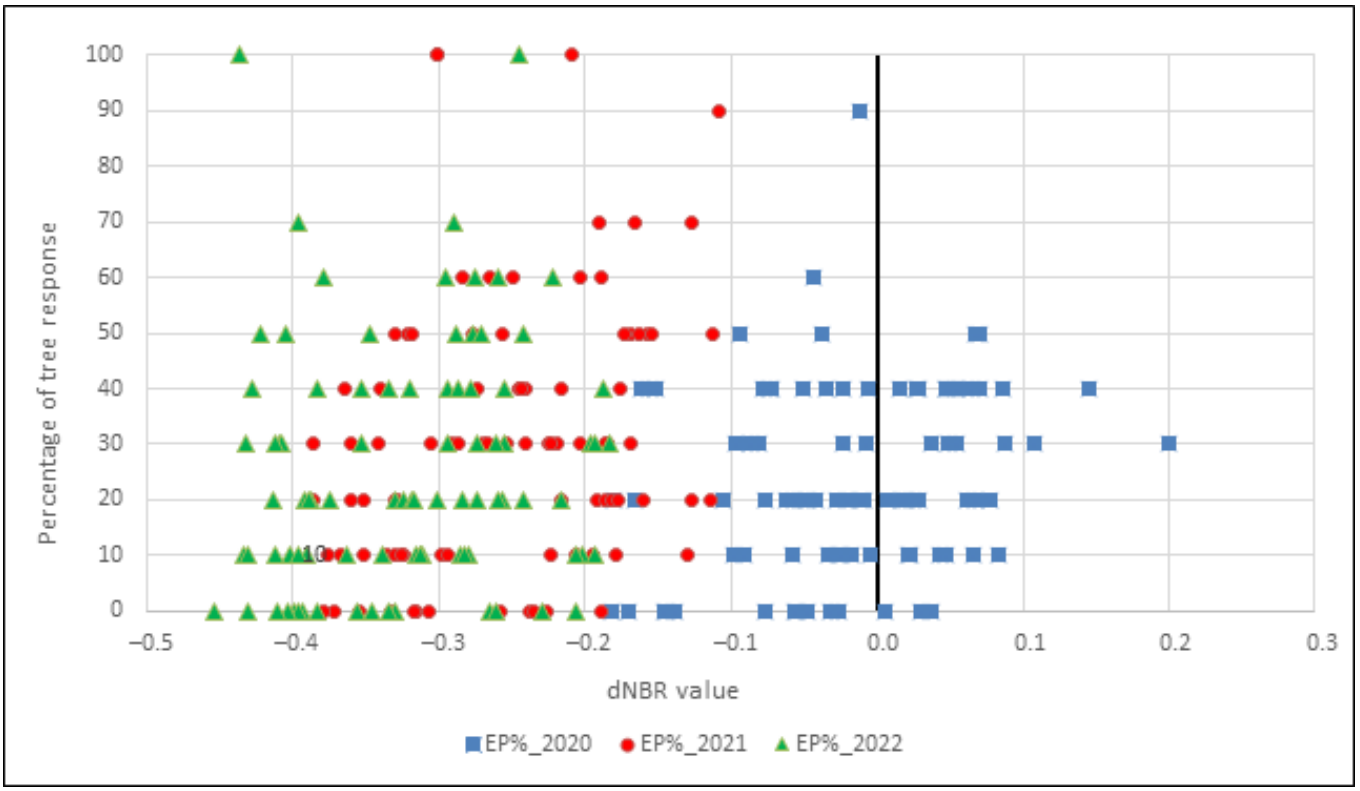


Figure 11. Tree recovery responses from epicormic shooting versus dNBR value for each of 88 plotless sites within the local study area over three years for all forest types.

4. Discussion

4.1. How Much of Each Koala Habitat Forest Type Was Burnt on a Regional Scale, and How Severe Was the Burning?

Fires impact different types of forests worldwide; for example, they affect the habitats of the woodland caribou [2] in Canada. Fire also impacts several arboreal mammals in the Brazilian Cerrado [68], which is not as fire-resilient as other vegetation types in that region, such as savannah and woodlands. In eastern Australia, different eucalypt forest types are likely to provide varying habitat quality and resources for the koala [63], so their responses to wildfire in terms of vulnerability and resilience could be important for the koala. We found that the five preferred koala habitat forest types in our study comprised

only 2% of a 12,000 km^2 area, which illustrates the paucity of preferred koala habitats [14] in the region. A total of 10% of all koala habitats that we studied were burnt. An even more significant proportion of GBS was burnt (32%), and 10% was severely burnt. In a study on koala habitats on the NSW North Coast, Australia, modelling by Phillips et al. [17] revealed that koalas were five times more likely to survive in areas with unburnt or partially burnt forest canopies compared to areas with fully burnt canopies. Of the five forest types we studied, GBS was far more significantly affected by fire and contains *Eucalyptus tereticornis* subsp. *basaltica* (mountain blue gum), regarded as a primary food tree for koalas [14,69]. Therefore, the fire event in 2019 was likely to have driven relatively large numbers of koalas from this habitat type to adjacent refuges, if available. At least 15% (898 Ha) of GBS experienced a high to severe fire impact, while only a combined 3% (140 Ha) of the other koala habitat REs studied (IPR, IBM, BFA, and BCF) were impacted by high-to-severe burns. Reducing the severity of large, catastrophic fires improves the survival chances of koala populations [70,71]. Other Australian arboreal mammal species are also at risk of displacement from their preferred habitats, such as the greater glider (*Petauroides volans*), which prefers mountain ash (*Eucalyptus regnans*) forests to other eucalypt type forests [72]. These mountain ash forests are at an increased risk of wildfire [73], and hence the habitat of the greater glider may also be at risk.

The presence of stringybark eucalypts, as opposed to smooth-barked eucalypts, presents a likely flammability hazard for many forest types [74,75], so a forest without stringybark species may provide a safer habitat for koalas and many other fauna species under fire-season conditions. Gill and Ashton [74] found that the relatively coarse, stringy bark of *Eucalyptus obliqua* caused greater heat penetration to the cambium than two other eucalypt species that had subfibrous bark and decorticating bark, respectively. Collins [75] found that eucalypts with fibrous bark were more prone to topkill. The vulnerability of fibrous-barked eucalypts to fire is uncertain, though, as Nolan et al. [21] found, the eucalypts most resistant to topkill have thick bark but low density. Further, in a South African study, Higgins et al. [76] did not find a relationship between bark thickness and topkill, but the species studied were not eucalypts. In our study, we found that the forest type IBM, which does not have stringybark as one of its major component species, was affected by fire to a much lesser extent, with less than 1% being severely burnt, even though it occupies similar terrain to GBS. There are two possible reasons that IBM burnt less: the trees in this forest type likely have lower bark flammability, and this forest type grows on finer-grained substrates like microgranite rather than granite (Queensland Department of Natural Resources, Mines and Energy) [77], so the corresponding soils are probably less well-drained, more fertile, and promote a greener and denser ground layer, which would be less flammable [78,79]. This forest type therefore serves as a less hazardous habitat than GBS, and this appears to be what we observed. It also occupies about twice as much area across the region than GBS does (33,000 Ha vs. 15,000 Ha), so this is a benefit for the koala.

In a study on an area of eucalypt forest in Tasmania, Ndalila et al. [80] found that fire severity was strongly influenced by terrain and vegetation type, which are likely to affect local arboreal fauna in the same way koalas are affected on the Australian mainland. In our study, the ridge-top forest type IPR was affected by fire to a much lesser extent than RE GBS, with only about 0.3% of it having been severely burnt, but it is subject to the inherent hazard of more limited routes of escape for koalas since fires generally tend to run uphill towards ridges [80], and access to the refuge of waterways and cooler gullies is more difficult. The optimal koala habitat therefore needs to have more of the advantageous qualities of REs to reduce fire hazards and increase the chance of escape to refugia. The upland forest types in our study (GBS, IPR, and IBM) have the inherent disadvantage for koala habitats of being located on hills or ridges and therefore vulnerable to ascending flames, as well as having flammable stringybark or a drier ground layer. Therefore, an alluvial landscape is likely to provide a less hazardous habitat for the koala. By far, the least fire-affected forest types in our study were the two on alluvium, namely, BFA and BCF, where much less than 1% of the area was burnt in each. These two forest types have

all of the advantages that the others in our study lack and occupy relatively large areas (about 40,000 Ha each) across the bioregion. However, the inland alluvial BFA is under pressure from agricultural and pastoral clearing, and the coastal and sub-coastal equivalent of it, BCF, is more under threat from residential development [19]. Nevertheless, these low-lying areas of forest on floodplains and in valleys and gullies are likely to be of higher habitat value to the koala after a fire. In a study conducted in South-Eastern Australia, which is also within the distribution of the koala, Chia et al. [81] found a higher abundance of arboreal mammals in forested gullies rather than on slopes.

4.2. Where Are the Fire-Free Refugia for Koalas in Our Study Area?

Refuges allow immediate survival for animals escaping from fires, providing habitats for individuals and populations post-fire, and enable long-term population recovery [82]. Koalas have been documented to recolonise nearby burnt areas within months [62]. However, severe fires can limit the amount of available refuge to more sheltered areas [83]. We confirmed this with our observations of GBS, which occurs on drier upland areas. Of the five forest types we studied, GBS occupies most of these upland areas, and about 67% of this RE remained unburnt. Although this constitutes a relatively large proportion of the overall RE area, the other REs studied were almost completely unburnt. Because of the overall negligible impacts of fire on the two lowland alluvial forest types BFA and BCF in our study, these present themselves as more suitable areas of post-fire refuge. Other areas of refuge, as identified by our mapping (Figures 4 and 5), include some of the other REs, but the alluvial REs appear to be the most suitable. However, these alluvial areas are not always near the burnt upland areas, so parts of these unburnt upland areas may function as the most immediate refuge [84].

In a study on Leadbeater's Possum (*Gymnobelideus leadbeateri*) in South-Eastern Australia, Durkin et al. [85] found that population recovery depended mainly on in situ survival and not external recolonisation. A study in Victoria conducted by Berry et al. [86] found that refuges of unburnt peninsulas extending into burnt areas helped some species to persist within extensively burnt landscapes (including the mountain brushtail possum, *Trichosurus cunninghami*) but not others (such as the greater glider, *Petauroides volans*). This suggests that the home ranges of individual species are important when responding to a wildfire, and the koala is fortunate to have a home range [62] that is relatively large compared to the ranges of other arboreal mammals such as the greater glider [86]. Koalas' home ranges are variable and have been observed to account for as much as approximately 14 Ha [63] of remnant forest near Kenilworth, Queensland, Australia, or as much as approximately 45 Ha [87] of an urban area in Lismore, NSW, Australia. Koala home ranges can be even larger, as found by Matthews et al. [62] in a remnant forest in Port Stephens, NSW, Australia, with up to approximately 70 Ha for males and up to approximately 34 Ha for females. This variation is probably due to overall habitat quality and other environmental influences. Most 4 km buffers around the burn areas in our study had koala records [51], so it was assumed that most of the refuge areas within those buffer zones were useful as koala refuges, as they are within the average koala's home range [62]. We found that there were no cases where a koala would have had to travel more than 4 km to escape from a burnt area (Figures 4 and 5), and in most cases where koalas had been recorded [51], the distance was much less. This is fortunate for the koala, but larger, more extensive wildfires may create unfeasible travel distances if climatic conditions are unfavourable.

The mapping in our study is intended to assist with the prioritisation of areas of refuge such as that established in the work carried out by Wilson et al. [88]. Landscape characteristics also need to be taken into account [89–91], such as cleared-edge effects and available water. Heterogeneity of burn patterns within the site may also be a factor in refuge selection [92], so in some cases in our study, adjacent refugia were possibly not as important as in situ refugia. Burnt areas can also be used for shelter, as has been observed by Matthews et al. [93]. Tree utilisation can be influenced by factors other than food value, such as security [17] and height [63]. Conservation area planning accounting for these

considerations would be best supported with tools like Marxan software [94,95] and can take current koala populations into account when prioritising refuge areas.

4.3. Do Some Koala Habitat Forest Types Take Longer to Recover than Others in This Region?

Different forest types can be expected to respond differently to fire, both in terms of vulnerability and resilience [18,22]. This difference in response can result in different recovery times for each particular forest type [96], and this is of significance for fauna habitats, both resident and transitory. In our study, the forest type (RE) GBS experienced the most severe fire impact in 2019 and provided a relatively poor habitat for koalas in the first year of recovery. In that time, koalas needed to find areas of refuge in other REs until the GBS recovered. However, the comparatively rapid recovery of the GBS indicates that it probably became a suitable source of food again relatively rapidly and was most likely in a state of new foliar growth from epicormic shooting and coppicing [18]. This rapid recovery was also observed in studies by Matthews et al. [62,93] conducted in Port Stephens, NSW, Australia, and by Law et al. [24] in North-East NSW, Australia. In our study, the trees themselves were most likely unsuitable for roosting due to a lack of shade (Johnson, pers. obs.), so the use of these habitats was probably transitory, with concurrent use of adjacent habitats for roosting. This was indicated by the widespread presence of koala scat without simultaneous sightings of koalas (Johnson, pers. obs.). Studies by others on forest recovery found that koalas returned to burnt habitats within several months. Matthews et al. [93] found that within three months after a wildfire, koalas were seen among the epicormic growth. Law et al. [24] noted that koalas were temporarily extirpated wherever high fire severity dominated the landscape, but some localised recovery was evident after one year. This is consistent with our results.

Eucalypt forests can recover from fires via epicormic shooting, coppicing, and seedling production, depending on the eucalypt species [18,22] and fire severity [97]. All of our dNBR analyses found that whilst all the forest types studied had recovered noticeably in the first and second years, the amount of vegetative recovery detected did not change in the third year of recovery, which suggested that foliage production had slowed or matured. As with the results from the NDVI, the dNBR can probably only measure general vegetation conditions, including understorey growth, ground layer, and possibly weeds, in addition to tree canopies, and do not necessarily indicate tree recovery via epicormic shooting and coppicing [18]. This under-representation of the dominant tree stratum was also observed by Cansler and McKenzie [98]. The two metrics were also unable to reliably detect the proportion of epicormic shooting, coppicing, and apparently dead trees killed by the fire. This means that the NDVI and dNBR should not be solely relied upon for an indication of koala habitat recovery, as it may not be eucalypt foliage growth that is being detected, and this is the critical resource for the koala. Field verification is necessary to confirm what the increases in NDVI and dNBR actually represent, unless more-definitive measures can be used to differentiate the various plant functional traits, such as hyperspectral analysis [99]. The use of remote sensing with resolution higher than that of Sentinel-2 may allow the detection of these particular types of regrowth via patterns and/or wavelengths. There is not much more in the way of field data that could be collected to improve the current relationship between the Sentinel-2 data and field-derived indices such as the GeoCBI. Drone imagery or LiDAR may also be appropriate, but the regional scale of this study indicates that hyperspectral imagery is probably the most practical and affordable. An improved ability to discern the extent and amount of recovery via epicormic shooting and coppicing would enable habitat recovery mapping to identify more fire-resilient areas of koala habitats.

5. Conclusions

The use of GeoCBI as a dNBR classifier effectively separated fire severity impacts and clearly identified the forest type GBS as the koala habitat most severely affected by fire. The study of forest recovery required manual classification (CISR) that was sensitive enough

to detect foliar regrowth. Our study found that the most suitable koala habitat in SEQ, Australia, occupies only about 2% of the region, and of that limited area, about 10% of it was burnt by wildfire in late 2019. This represents a very limited safe habitat for the koala, and refuges in wetter alluvial areas are important for its ongoing survival (e.g., the forest type REs BFA and BCF). Unfortunately, these alluvial areas are under pressure from agriculture, grazing, and clearing for development. However, the conservation of the other forest types studied is equally important. Forest types on hills were found to be more susceptible to fire, but they are good refuges from the extensive land clearing occurring on the alluvial areas. Each of these three forest types on hills has its own advantage: GBS was most severely and extensively burnt but recovered quickly; IPR on ridges would be hazardous for the koala in terms of escape from fire but accounted for the most area of all the REs studied within the bioregion; and IBM also comprises quite a large area that did not burn very extensively. We found that the dNBR can probably only measure general vegetation present and not specifically tree recovery from epicormic shooting and coppicing. Eucalypt foliage growth is the critical resource for the koala, so field verification seems necessary unless more-accurate remote sensing methods such as hyperspectral imagery can be employed.

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