scientific reports

OPEN

Quantifying forest degradation, deforestation and land use change in vital swift parrot breeding habitat

Giselle Owens✉, Robert Heinsohn, Philip Gibbons & Dejan Stojanovic

Forest degradation is a major cause of habitat loss for species that rely on old forest features. Quantitative knowledge of forest degradation and deforestation in the breeding range of the critically endangered swift parrot (*Lathamus discolor*) is poor but essential to inform effective conservation planning. We provide the first quantitative analysis of forest degradation and deforestation across the swift parrot breeding range. We identify trends and drivers of anthropogenic loss to determine whether current forestry policy is aligned with targets to secure species recovery. We used global datasets of forest extent, change and loss to evaluate historic deforestation and forest dynamics since the year 2000. We applied our analysis at three spatial scales within the breeding range: potential, core, and Swift Parrot Important Breeding Areas (SPIBAs). We measured trends in fire and anthropogenic forest loss before and after forestry policy changes. Results informed a land use change analysis to identify major drivers of forest loss. Habitat loss has occurred in more than 50% of the swift parrots' breeding range. More than 37% of the breeding range was permanently deforested prior to the year 2000. Of remaining forest in the year 2000, approximately a quarter has been disturbed, degraded or permanently deforested. Degradation was 6.5 times that of deforestation, and production forestry was the major human driver of forest loss. Forest loss rates in SPIBAs have doubled since forestry policy change in 2014. Degraded forests are unlikely to provide habitat for swift parrots and urgent changes to forest policies and practices are needed to ensure the perpetuity of the species. We highlight the advantages of using publicly available remote-sensing datasets to quantify past and present habitat degradation, deforestation, and land use change at biologically meaningful scales relevant to the recovery of threatened species.

Reducing deforestation and forest degradation is a focal objective of many environmental agendas, including arresting biodiversity loss, reducing emissions and tackling climate change. Most tree loss globally (62%) is temporary via degradative processes (e.g. forestry, tree plantation rotation, wildfire) and the remainder is permanent[1]. Whereas deforestation is the permanent conversion of forests to non-forest land uses, forest degradation can be defined as a reduction in a forest ecosystems structure, function, composition and capacity to provide ecosystem services[2,3]. Quantifying degradation has been more challenging to quantify than deforestation as canopy cover may be partially impacted or regenerate over time[2,4]. Forest change analyses often rely on satellite imagery data of 'forest loss', which encompasses both temporary and permanent stand-removing disturbances[5]. Recent advancements in remote sensing data and analytical techniques have facilitated more nuanced spatial analyses capable of distinguishing between anthropogenic and fire-driven forest loss, while also identifying degraded and disturbed forests[1,6]. This differentiation is vital for informing effective conservation and land use policy, as forest loss from increasingly altered natural processes, such as wildfire[6], and anthropogenic drivers, including forestry, agricultural expansion and urbanization[7,8] can compromise forest quality via fragmentation[9], changes in structure[10], altered species composition[11], edge pressures and heightened susceptibility to subsequent disturbances[12,13].

Forest degradation and deforestation pose a key threat for biodiversity via the removal and diminishment of mature habitat[14]. A comprehensive study of extinction risk for 19,432 vertebrates worldwide revealed that forest loss elevates the risk of a species being listed as threatened on the IUCN Red List, of being upgraded to higher threat categories and experiencing population decline[15]. Forest-dependent species are highly vulnerable to forest

Fenner School of Environment and Society, Australian National University, Canberra, ACT, Australia. ✉email: giselle.owens@anu.edu.au

loss[8], with numerous additional species projected to be classified as threatened due to globally prevailing trends of forest management[15]. For example, parrot species that have the highest risk of extinction have high forest dependence, are island endemics and are impacted most by logging, agriculture, trapping and hunting[16]. With climate change and land-use change projections affecting forests, including protected areas[17,18], the potential risk presented by forest degradation to biodiversity might outweigh that of outright deforestation at regional scales[11]. Conservation programs aimed at halting the loss of forest-dependent species therefore require critical evaluation of both deforestation and forest disturbances that degrade forests. Furthermore, identification of the underlying land-use drivers is a priority for planning mitigation efforts, along with an evaluation of the efficacy of existing policies in maintaining forest quality for these species.

Certain forest-dependent species, such as those that rely on old forest features (e.g. tree cavity-nesters) are especially affected by forest structural changes[16,19]. Throughout the last two centuries, the nomadic swift parrot *Lathamus discolor* has faced significant habitat loss across its range in south-eastern Australia[20]. It breeds only in the island state of Tasmania, where it continues to be impacted by forestry[21]. The swift parrot requires extensive forested area as the distribution of food resources (i.e., flowering eucalypts) vary spatially each year across its breeding range[22] and nearby nesting sites (i.e., specialized tree cavities in old trees) are scarce[23,24]. The loss of key habitat resources and intactness renders the parrot at elevated risk of concurrent threats (e.g. invasive species pressure, climate change), unabated population decline and extinction[25,26].

Forest degradation from human-uses is equivalent to habitat loss for the swift parrot. Regenerated trees from forestry practices are unlikely to attain an age or size that provide tree cavities suitable for nesting (120–220 years)[19,24] or substantial food resources (i.e., the mean diameter-at-breast-height (DBH) of foraging trees is 84 cm, young trees with mean DBH ≤ 59 cm are not foraged)[27], based on the comparatively short time span of silvicultural rotations in native forests (< 90 years)[28]. Variable retention silvicultural practices, such as the retention of mature habitat clumps, are practiced in some harvested areas and may provide resources for some forest species (e.g. brushtail possums *Trichosurus vulpeculai*). However, this measure is likely to be insufficient to meet the needs of the swift parrot, as retained clumps in Tasmanian forests are small (mean 0.1ha, < 0.21 ha), have elevated rates of tree collapse post-harvest (11.7%/10 years)[29,30], and have a small probability of containing a cavity suitable for swift parrots[24,31]. *Eucalyptus* plantations are also unlikely to provide food for swift parrots as plantations are harvested on even shorter rotations (30 years)[28]. Based on current practices, cleared and regenerating forests, (i.e., degraded and disturbed forests) represent a detrimental, long-term loss of habitat for the swift parrot population.

To guide swift parrot habitat retention, a report in 2010 identified 12 'Swift Parrot Important Breeding Areas' (hereafter SPIBAs)[32]. SPIBAs were selected as priority management areas based on known use and suitable habitat, and a further three have been added since. By 2015, estimates of a severe population decline[33] resulted in uplisting the swift parrot to 'Critically Endangered'[34]. A key management recommendation to avert extinction was the management and protection of known swift parrot habitat at the landscape scale with the goal of achieving a sustained population increase over 10 years. Nevertheless, the swift parrot population has continued to decline[25], with fewer than 500 individuals remaining[35]. Recently, the Australian Government committed to averting extinction of swift parrots[36,37], which calls into question whether forest policies currently in place across Tasmania support or exacerbate the swift parrot's negative population trajectory[38]. Moreover, Australia has signed global commitments to halt forest degradation and deforestation by 2030 (i.e. the Glasgow Leaders' Declaration on Forests and Land Use)[39]. To date, no quantitative range-wide assessment of habitat loss has been undertaken for the swift parrot, although it has been a listed action in recovery plans for more than a decade[40,41].

Quantifying forest degradation and stand-disturbance (e.g. partial canopy loss, height reduction, thinning) in landscapes that remain forested (by regenerating woody growth) presents challenges. Data on forest quality are not captured by satellite imagery of tree cover extent, but these data can be aggregated with thematic maps for further inference. The swift parrot's breeding range exemplifies this challenge, as Tasmania has 72–76% vegetation cover[42], but only a third of Tasmanian forests remaining are intact[43] or of high integrity[13,25]. Within swift parrot important breeding areas (SPIBAs), forests with high integrity are even scarcer (4.2% vs. 29.4% statewide)[25]. Forest accounting (i.e. systematic measurement and tracking of forest condition and changes over time) in swift parrot habitat is complicated by shifts in land-use classification in forested areas following a policy change enacted a decade ago through the *Forestry (Rebuilding the Forest Industry) Act 2014*[44]. This policy's purpose was to "provide for the invigoration of the forest industry and for related purposes", thereby repealing prior legislation that sought to protect forests of high conservation value (i.e. the *Tasmanian Forests Agreement Act 2013*). Subsequently, high conservation value reserves were reclassified as production forestry land and previously used forestry land was converted into reserves[21].

Current zonal maps used to guide and report on forest management, such as reserve area and timber production zone land[45], therefore do not account for legacy effects of forest degradation and deforestation. Subsequently, the true extent of habitat loss that has occurred within the swift parrot breeding range is likely to be underestimated. Fortunately, advances in satellite imagery processing in the last decade[5] have enabled transparent analysis of multi-decadal forest loss and change since the year 2000 (noting that by this time, extensive unquantified deforestation and forest degradation had already occurred in Tasmania)[20]. More recently, technological advances have enabled the disaggregation of fire-driven loss from other drivers of forest loss[6], as well as the detection of tree height changes, forest clearing and other forms of forest disturbance[1].

Conservation of the swift parrot will require protecting extant forest in its breeding range from deforestation and degradation. To achieve this, it is necessary to evaluate if current land management trends and policy are supporting this objective. We aim to provide the first quantitative analysis of deforestation, degradation and forest loss (i.e. stand-disturbance) across the entire swift parrot breeding range. We sought to identify the drivers of forest loss and to identify trends since policy change. We conducted our study at: (i) the breeding range level, given the importance of crucial feeding and nesting habitat to a mobile species' survival and subsequent assessment criteria (i.e. area of occupancy [AOO], extent of occupancy [EOO]) on the IUCN Red List, and (ii) at smaller core range and SPIBA levels, given the intended purpose of these spatial units to guide forest management for this species.

Methods

The swift parrot's breeding range is in the island state of Tasmania, Australia. Current swift parrot range boundaries are predominantly in the east and north, with small pockets in the west of the state (Fig. 1). Major land uses include production forestry of native forests, plantation forestry, agriculture and pasture, and conservation areas[42]. *Eucalyptus* tree species dominate dry and wet sclerophyll forests and include medium to very tall species (e.g. *E. globulus*, *E. obliqua*, *E. delegatensis*, *E. viminalis*, *E. regnans*) that typically reach heights in excess of 45 m and up to 80–100 m[46]. Small-medium trees, such as *E. ovata* and *E. brookeriana*, reach 30–40 m in height[46].

We used global datasets that enable consistent spatial and temporal analyses of forest extent, change and loss as the foundation of our analysis. These data are produced from Landsat data by the Global Land Analysis

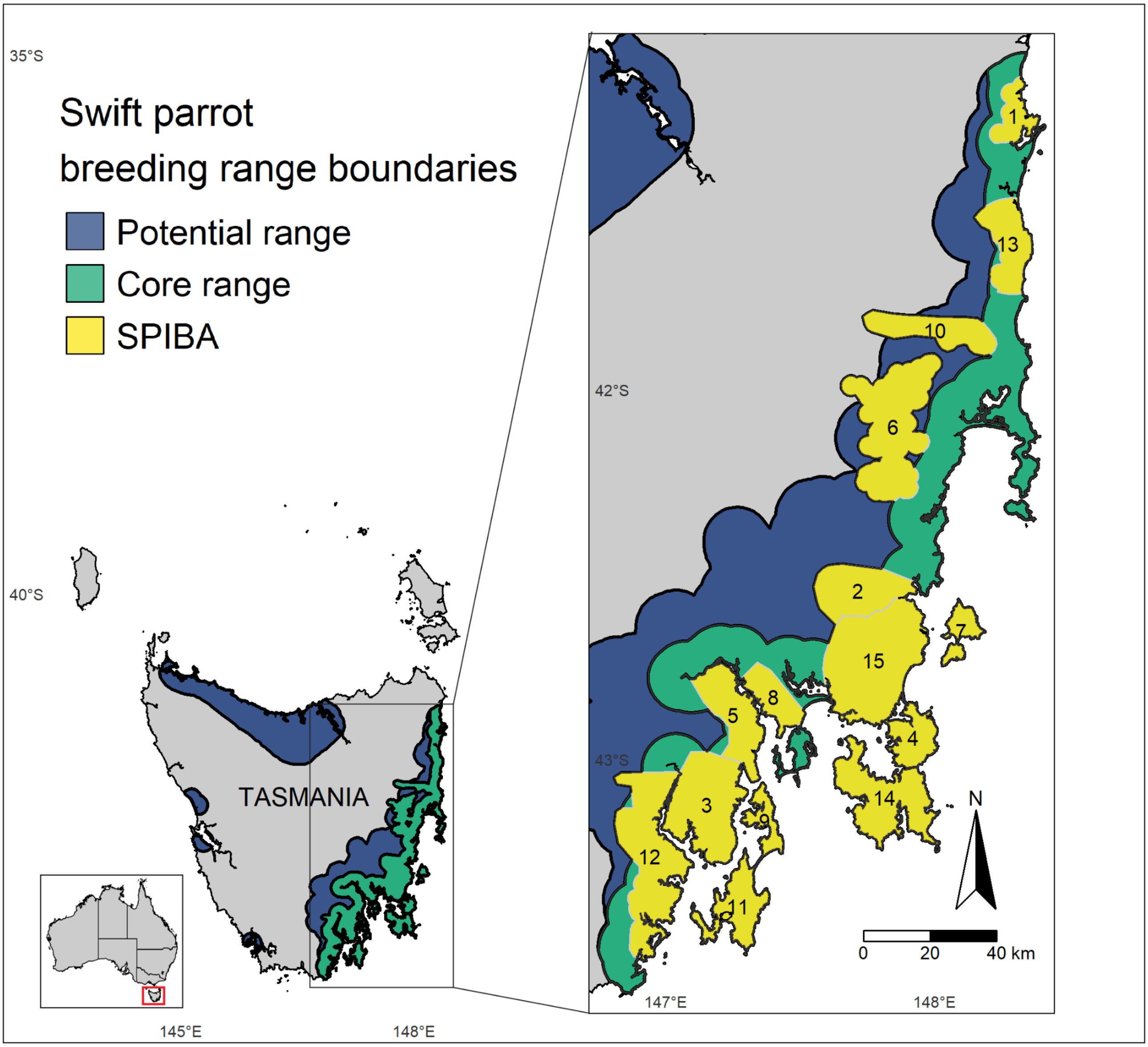

Fig. 1. Breeding-range boundaries for the migratory swift parrot *Lathamus discolor* in Tasmania, Australia. 'Potential range' (dark blue) denotes the extant breeding range. The 'Core range' (green) contains Swift Parrot Important Breeding Areas (SPIBAs) (yellow), which are management boundaries to prioritize swift parrot habitat protection. There are fifteen SPIBAs: 1 – Binalong; 2- Buckland; 3- Channel; 4 – Forestier Peninsula; 5 – Hobart; 6 – Lake Leake; 7 – Maria Island; 8 – Meehan Range; 9 – North Bruny; 10 – Royal George; 11 – South Bruny; 12 – Southern Forests; 13 – St Marys; 14 – Tasman Peninsula; 15 – Wielangta[32]. Map generated in R[52] with publicly available swift parrot management boundary datasets[32] and packages *sf 1.0–14*[50,51], *tmap 3.3-4*[55]and *viridis 0.6.4*[56].

and Discovery (GLAD) team at the University of Maryland and are publicly available (https://glad.umd.edu/dataset). Forest change analyses within breeding habitat were undertaken in Google Earth Engine (https://earthengine.google.com), which enables cloud processing of large datasets using JavaScript. Forest height, extent and disturbance dynamics between the years 2000 and 2020 were quantified with the Global Land Cover and Land Use Change (GLCLUC) dataset[6]. As this dataset does not yet provide annual data necessary for trend analysis, we used commonly used spatial datasets of forest loss[5,6], which define forest loss as a stand-replacement disturbance (i.e. loss followed by regeneration; degradation) or a permanent removal of the canopy ≥ 5 m (i.e. deforestation). Specifically, inter-annual variability and trends in forest loss from fire and non-fire causes between the year 2000 and 2022 were derived from the Global Forest Change dataset[5] and 'Global forest loss due to fire' map[6]. Drivers of forest loss from non-fire causes were identified with a land use and land change analysis of classified spatial data (Tasmanian Land Use 2001; Tasmanian Land Use 2021)[47,48] (https://www.thelist.tas.gov.au/), defined by Australian Land Use and Management (ALUM) classes (https://www.agriculture.gov.au/abares/aclump/land-use/alum-classification). ALUM class data are verified and validated at catchment scale following national guidelines[49].

The boundaries of SPIBAs, core and potential ranges (Fig. 1) (available from the Natural Values Atlas (https://www.naturalvaluesatlas.tas.gov.au/) were intersected with major vegetation classes using regional mapping data of vegetation groups (TASVEG 4.0) (https://www.thelist.tas.gov.au/), and package 'sf' v.1.0–8[50,51] in R[52]. We used swift parrot range boundaries and vegetation types as overlays on the forest change datasets. Current vegetation maps include the class 'modified land' (e.g. plantations, agriculture, urban areas, etc.), which encompasses land that was previously eucalypt forest and has been modified, either historically or recently (i.e. prior to the year 2020). We therefore included all vegetation classes in our analysis of forest status and calculated the proportion of forest area per class. To estimate historic deforestation, we used national thematic maps (NVIS 6.0) of major vegetation groups at two time points: prior to the dispossession of the Palawa/Pakana people of their country ('pre-1750'), and this century ('present')[53,54] (Fig. 2). Datasets and associated spatial resolution are listed in Table S1.

Forest height, loss and disturbance

We used the Global Land Cover and Land Use Change dataset[1] to quantify change in forest height and extent. The height of forests is a useful way of detecting degradation that does not result in deforestation. For example, logging of old growth forest often results in rapid replacement by shrubs and saplings, resulting in ongoing forest cover of diminished habitat value. Forest area was calculated from height maps for forest ≥ 5 m height in the year 2000 and the year 2020. We stratified forest extent at 5–9 m (short), 10–19 m (medium) and ≥ 20 m (tall) for years 2000 and 2020 per Potapov et al. (2022) (i.e. classification thresholds, 0,5,10,20,>20). The lower-bound limit of the tallest stratum category is restrained at ≥ 20 m as pixel resolution (30 m; Table S1) is saturated at taller heights[1]. These categories are therefore not intended to match alternative definitions of forest heights, which vary globally and by forest type. Gross loss and gain dynamics of forest height extent were calculated across

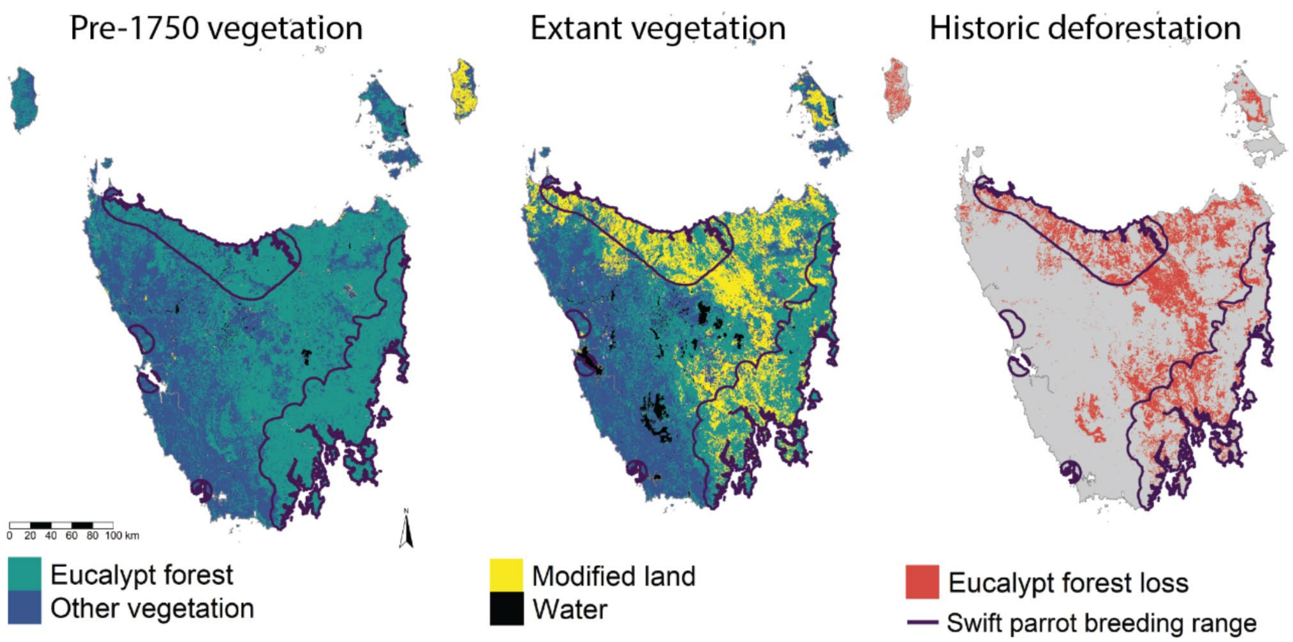

Fig. 2. Historic change in vegetation cover and eucalypt deforestation in the swift parrot breeding range in Tasmania[53,54]. Dark purple lines represent the swift parrot breeding range, defined by current 'potential' range boundaries[32]. From left to right, vegetation cover prior to the year 1750, extant vegetation cover and historic deforestation of eucalypt forests. Map generated in R[52] with packages *raster 3.6–26*, *sf 1.0–14*[50,51], *tmap 3.3-4*[55]and *viridis 0.6.4*[56].

time-points. Stable and dynamic forest extent were quantified using the dynamic forest type map by Potapov et al.[1] This classifies forests into four types: (1) stable forests with no to minimal height change; (2) forest extent loss, equivalent to loss of trees ≥ 5 m height in the year 2000 without replacement; (3) forest extent gain, growth of trees ≥ 5 m since the year 2000; (4) forest loss and disturbance, equivalent to forests which experience stand-level disturbances, height loss ≥ 50%.

Trends and interrupted time-series analysis

We employed an interrupted time series analysis[57] to assess the impact of policy change on forest loss over a 22-year period, from the years 2001 to 2022. Interrupted time series analyses are typically used to assess the impact of a law or policy or treatment following an event[57]. The interruption point corresponded to the year 2014, when the policy change (i.e., the *Forestry (Rebuilding the Forest Industry) Act 2014*) was implemented. This approach allowed us to assess whether there was a significant change in forest protection or loss in the swift parrot breeding range following the policy change and the prevailing trends. For this reason, we collected annual time-series data on forest loss in SPIBAs from the Hansen Global Forest Change 2000–2022 dataset, as the Global Land Cover and Land Use Change dataset currently does not provide annual data. We utilised these data to identify the first stand-replacing loss per pixel across all years. We used this map in conjunction with the 'Global fire loss due to fire' 2001–2022 map, to disaggregate fire-driven loss from anthropogenic (non-fire) drivers within the Global Forest Change dataset. We used only pixels classified with medium-high certainty as loss from fire, per Tyukavina's[6] classification of fire and non-fire loss. To capture trees in open woodland or heavily deforested areas, tree canopy cover was defined as canopy closure > 0% for trees ≥ 5 m height at 30 m pixel resolution. Prior to conducting the analysis, the data were explored visually with line plots. These plots provided an overview of temporal trends, vegetation cleared and fluctuations in fire and anthropogenic-driven forest loss.

We fitted segmented linear regression models on the interrupted time series data[57] of anthropogenic forest loss in *R*[52]. These included the following variables: forest loss (hectares) per year in SPIBAs; time variable t corresponding to year; interruption time coded as 0 pre-policy change and 1 post-policy change; and a slope change variable, equal to zero at the year of policy change (2014). We modelled predicted forest loss post-policy change and a counterfactual model (i.e. alternative trajectory) of estimated annual loss if the interruption had not occurred. Significance of the variables was assessed using standard t-tests for the coefficients.

Anthropogenic drivers

To identify dominant human drivers of forest loss in swift parrot breeding areas, we conducted a land-use and land change analysis within the impacted forest area. We used maps of Australian Land Use and Management (ALUM) classes at different time-points (2001, 2021)[47,48], in conjunction with SPIBA boundaries as overlays with the disaggregated anthropogenic forest loss data (i.e., the study area was defined by pixels of remotely-sensed anthropogenic forest loss within SPIBAs detected between 2001 and 2022 and excluded forest loss from fire). Zonal statistics of land-use and conversion in areas of anthropogenic forest loss in SPIBAs between 2001 and 2021 were obtained in R using package 'sf' v.1.0–8[50,51]. Land use classes were grouped by primary classification groups, except for secondary classes of known importance (e.g. production forestry, plantations, conservation and natural environments).

Results

Our analyses within swift parrot breeding habitat reveal changes in forest dynamics and trends over the last two decades. We estimated that approximately one quarter of forest within the breeding range of the swift parrot was disturbed, degraded or permanently deforested between 2000 and 2022 (Table 1). Forest degradation and disturbance (including stand-level disturbances and forests that had a canopy height reduction of 50%) was 6.5 times that of deforestation. The extent of degradation and disturbance varied across SPIBAs, with some areas (e.g., the Southern Forests) disproportionately affected. Anthropogenic forest loss (inclusive of stand-replacement and permanent loss) in SPIBAs has shown a significant and sustained increase since forestry policy changes in 2014, four years after the first SPIBAs were designated. Land use and change analysis shows that production forestry is the dominant anthropogenic driver of forest loss, followed by forestry in areas previously or subsequently managed for conservation, and conversion of native forest to plantations. Catastrophic wildfires

	Net forest area change		Net forest extent loss		Net forest extent gain		Forest loss, disturbance and degradation	
Breeding range boundary	Area km^2	%	Area km^2	%	Area km^2	%	Area km^2	%
SPIBAs	14	0.3	79	1.8	93	2.2	744	17.3
Core Range	4	0.1	115	1.9	119	1.9	962	15.5
Potential Range	-73	-0.5	462	3.4	389	2.9	3022	22.2

Table 1. Forest area (km^2) and dynamics within swift parrot range boundaries from 2000 to 2020. Forest loss, disturbance and degradation presented here includes forest extent loss and stand-replacing disturbances or a forest height reduction ≥ 50%, per the categories in the GFCLUC dataset[1]. Net forest gain refers to forests that grew ≥ 5 m since the year 2000 and net forest loss refers to removal of forest ≥ 5 m without replacement.

(e.g., in 2019) exerted high levels of temporary forest loss at regional levels but overall exerted less forest loss than non-fire drivers.

Forest status in 2020

As of the year 2020, there were 13,567 km^2 of forest cover across the swift parrot breeding range. Approximately 74% of forest cover is classed as *Eucalyptus* forests and woodlands, 14% of forests is classed as 'Modified land' and other vegetation classes make up the remainder of forested area (12%). Within SPIBAs, 83% of forest area is *Eucalyptus* forests and woodlands, 11% is modified land and 6% is composed of other vegetation classes. 'Modified land' includes land converted from native vegetation, including *Eucalyptus* forest, at any time prior to 2020. An estimated 37% of historic *Eucalyptus* forested land within current breeding range boundaries has been cleared and converted to modified land uses since European settlement (Fig. 2). Approximately 37% of forests in the swift parrot breeding range were above 20 m height in the year 2020 (Fig. 3). The distribution of tall forests was unequal amongst SPIBAs, with six SPIBAs having fewer than 20% tall forests and five SPIBAs being composed of more than 50% tall forest.

Forest dynamics

Forest area in the swift parrot breeding range was defined as forest and woodland with a canopy height ≥ 5 m, and included land categorised as modified uses and plantations, as either may have been intact forest in the year 2000. Within the potential breeding range, 3.4% of forest (462km^2) was cleared without stand-replacement and a further 18.8% (2633km^2) was affected by stand-replacing disturbances or forest height reduction ≥ 50% (i.e. forest disturbance and degradation) (Table 1). In the two decades 2000–2020, the net area of forest across the potential range of the swift parrot decreased by 0.5% or 73km^2. The net change is a balance between net extent loss (462km^2), defined as forest cleared without replacement by the year 2020, and extent gain (389km^2), representing forests that recovered to heights ≥ 5 m or established since the year 2000. During the last two decades, 2.9% of forests established or grew ≥ 5 m. Cumulative forest loss, disturbance and degradation were relatively similar at different spatial levels (15.5–22.2%), encompassing the SPIBAs, core and potential range (Table 1).

Some SPIBAs had disproportionately high rates of forest loss and disturbance compared to other breeding areas (Fig. 4). Forest loss and disturbance ranged from near zero within a national park (0.6% on Maria Island) and up to 35% in regions affected by intensive timber harvesting (35.6% in the Forestier Peninsula; 34.9% in the Southern Forests; 26.6% in Wielangta). Three SPIBAs (Southern Forests, Wielangta, Lake Leake) account for 43% of the SPIBA forested area, and each have more than ~ 550km^2 of forests. These same areas account for the most forest loss and disturbance compared to other SPIBAs: Southern Forests (198.6km^2); Wielangta (148.5km^2); and Lake Leake (Eastern Tiers) (84.9km^2) (Fig. 5). A third of SPIBAs experienced a small decline in forest extent (0-1.4%), most notably Lake Leake (5.6km^2) and the Southern Forests (3.5km^2). Remaining SPIBAs experienced a slight gain (0-2.2%) in forest extent, representing forests that grew ≥ 5 m or established since the year 2000, with the largest extent gains in the Channel (5.9km^2) and Wielangta (12.5km^2).

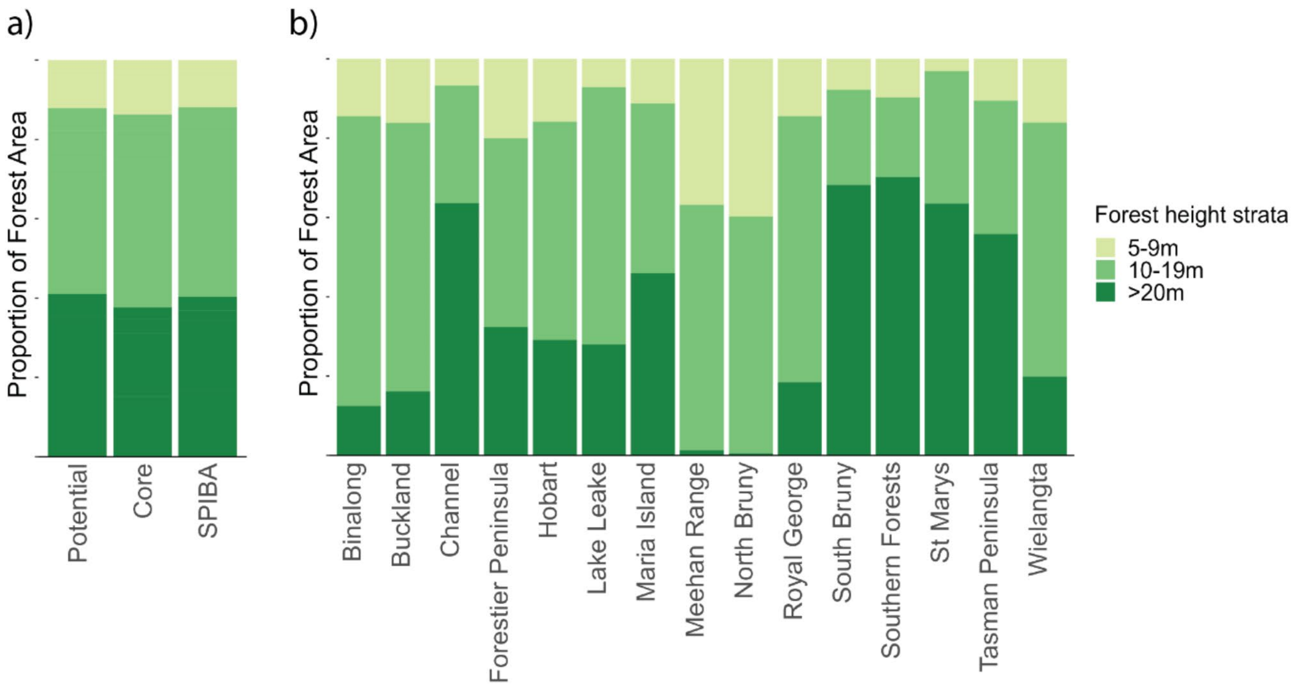

Fig. 3. Proportion of forest area by height strata in 2020 within (a) swift parrot range boundaries: Potential, Core, Swift Parrot Important Breeding Areas (SPIBA's); and (b) individual SPIBA's. Data: Global Land Cover and Land Use Change dataset[1].

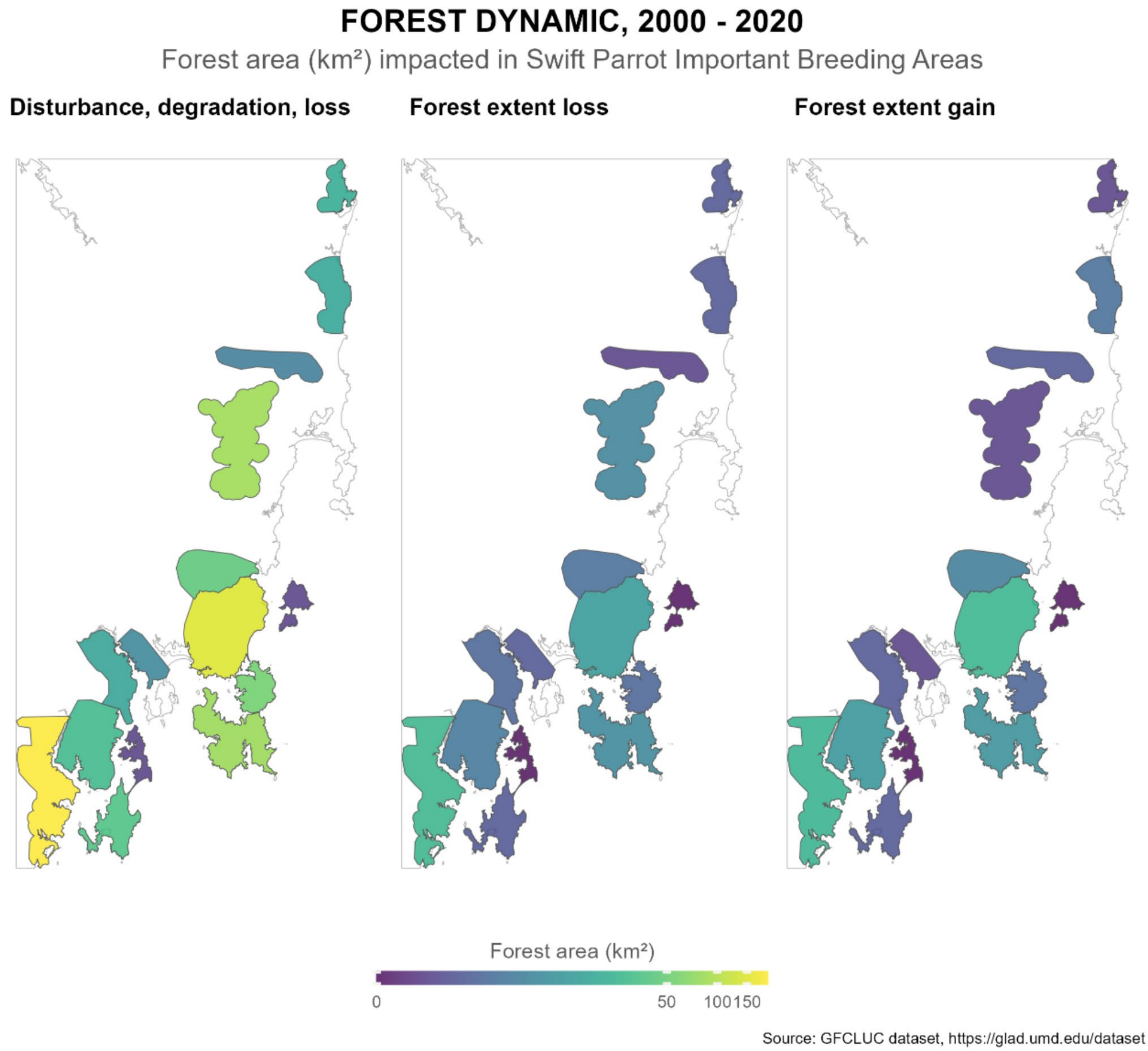

Fig. 4. Forest dynamic type in Swift Parrot Important Breeding Areas (SPIBAs) by forest area (km^2) impacted between 2000–2020.

The forest height data showed the distribution of short, medium and tall forests across the swift parrot breeding range. This information expands on simple metrics of loss and gain, reflecting changes in forest strata and dynamics of forest regeneration and forest enhancement (growth of pre-existing short-medium height forests since the year 2000). Forests were stratified by three height classes per Potapov et al. (2022) into short (5–9 m), medium (10–19 m) and tall (≥ 20 m) forests. Tall forests constituted 44.6% of the swift parrot's total breeding range in 2020, while medium-height forests occupied the most area (46%) and short forests represented 9.3% (Table 2; Fig. 3). Net height gain occurred in tall and medium forests (39.8km^2) across SPIBAs, indicating the transition from short and medium forests over 20 years, while net short forest extent correspondingly declined (71.3km^2). The 20-year net change in height classes represents the balance between forests that grew and transitioned height classes, stable forest heights per strata, and forest loss. Height-trends over twenty years were consistent across multiple-scales (i.e., potential range, core range, SPIBAs collectively) (Table 3).

The pattern of forest height gain and loss was more variable between SPIBAs. Some SPIBAs experienced an increase in tall forest extent (Channel, 18.2km^2; Buckland, 11.3km^2) and decrease in short forest extent. Five SPIBAs had net loss of medium-tall forests. The SPIBA with the greatest area of forest loss, disturbance and degradation – the Southern Forests – had a net loss of 16.4km^2 tall forest and a net gain of 12.8km^2 short and medium forests.

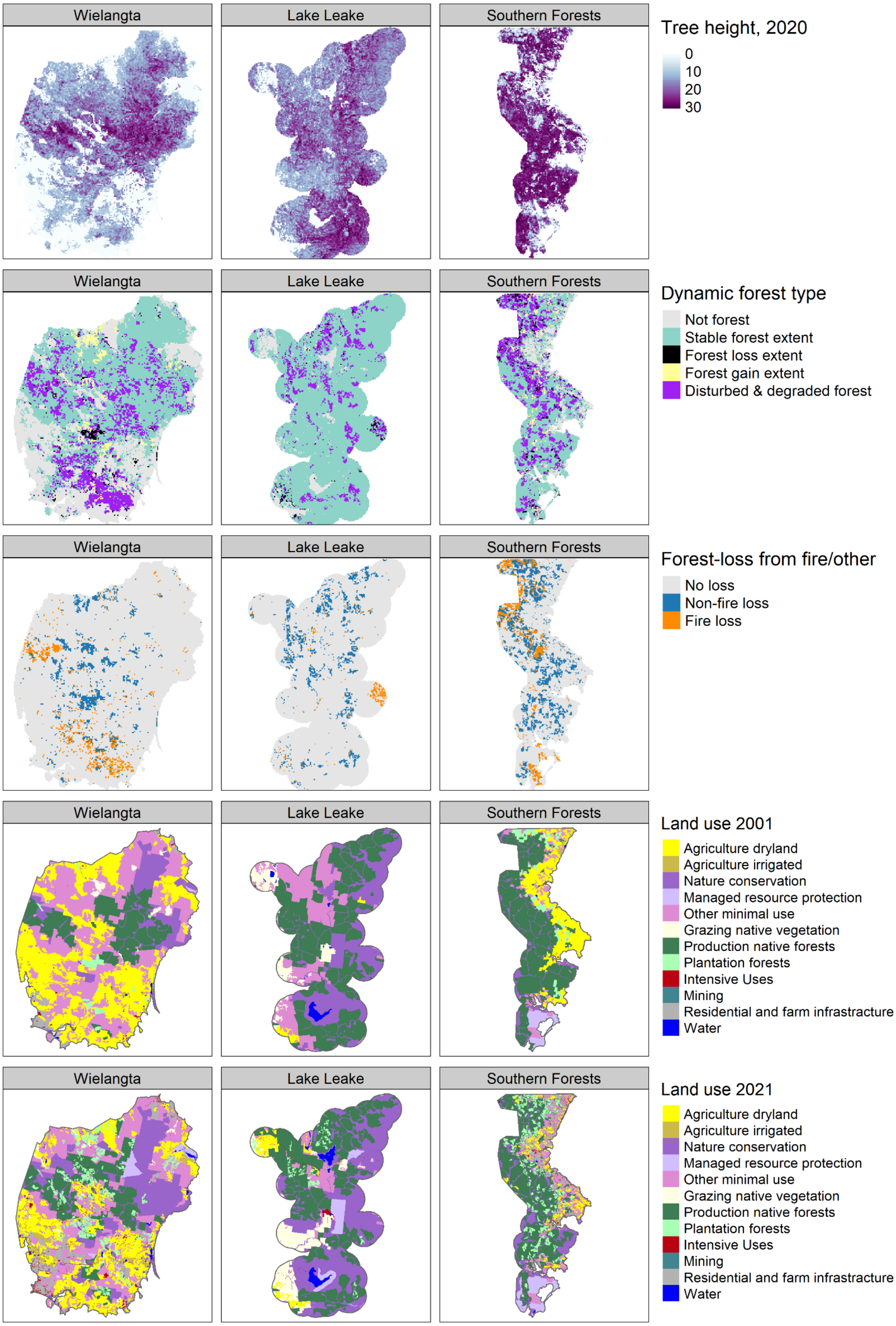

Fig. 5. Three most impacted Swift Parrot Important Breeding Areas (Wielangta, Lake Leake, Southern Forests), by: tree height (year 2020; Forest dynamic (Source: GLCLUC dataset[1]); forest loss from fire and non-fire (Source: GFC and 'Global loss from fire' datasets[5,6]), and; land use class in 2001 and land use class in 2021. Forest disturbance, degradation and loss in these areas totalled: Wielangta (89.7km^2): Lake Leake (Eastern Tiers) (58.8km^2); Southern Forests (106km^2).

SPIBA	Eucalyptus Forest Area km^2 Year 2020			Net forest change km^2 2000–2020		
	5–9 m	10–19 m	≥ 20 m	5–9 m	10–19 m	≥ 20 m
Binalong	11.1	79.3	22.5	-2.4	-3.9	5.4
Buckland	30.4	196.9	61.6	-13.2	4.0	11.3
Channel	23.7	110.1	277.8	-15.0	2.8	18.2
Forestier Peninsula	25.6	73.6	56.3	-2.1	5.4	-2.7
Hobart	33.2	120.0	76.7	-12.4	1.4	9.9
Lake Leake	35.8	421.1	243.1	2.8	-7.4	-1.0
Maria Island	7.3	35.4	46.8	0.5	-0.3	-0.4
Meehan Range	26.1	65.1	1.8	-7.8	5.9	0.6
North Bruny	13.6	35.9	0.7	-3.1	3.1	0.0
Royal George	20.4	146.8	50.9	7.3	-2.1	-3.6
South Bruny	14.9	46.0	151.7	-5.8	-0.8	6.6
Southern Forests	52.8	105.6	407.0	6.7	6.1	-16.4
St Marys	6.6	67.4	173.0	-1.2	1.7	1.6
Tasman Peninsula	33.5	117.4	220.2	-3.5	0.0	5.3
Wielangta	66.4	366.9	136.8	-22.1	23.7	10.9

Table 2. Forest height strata area and net change (2000–2020) within SPIBAs. Data source: Global Land Cover and Land Use Change dataset[1].

Breeding range boundary	Eucalyptus forest area km^2 Year 2020			Net forest change km^2 2000–2020		
	5–9 m	10–19 m	≥ 20 m	5–9 m	10–19 m	≥ 20 m
SPIBAs	401.3	1987.5	1927.0	-71.3	39.8	45.6
Core Range	658.0	2955.1	2598.9	-129.4	55.3	77.8
Potential Range	1327.8	6053.8	6180.6	-190.1	47.9	69.6

Table 3. Forest height strata area and net change (2000–2020) within swift parrot breeding range boundaries. Data source: Global Land Cover and Land Use Change dataset[1].

	Forest loss from fire		Forest loss from anthropogenic drivers	
	Area km^2	%	Area km^2	%
SPIBAs	167	33	346	67
Core range	264	38	436	62
Potential range	654	25	1952	75

Table 4. Forest loss from fire and anthropogenic drivers between year 2000 to 2022 within the swift parrot breeding range. Estimates are derived from the 'Global forest loss from fire' map[6] & the Global Forest Change map[5].

Annual trends and forest loss from fire

Years of forest loss between the year 2000 and 2022 were derived from the Global Forest Change map where loss pixels represent the first stand-replacement disturbance and may include either permanent forest loss or areas that later regenerate. Disaggregated annual forest loss from fire per loss pixel was obtained from the 'Global loss from fire' map[6] which is an expansion of the Hansen et al.[5] Global Forest Change dataset. Breeding range-wide, 75% of forest loss was attributable to anthropogenic, non-fire drivers and a quarter of loss was from fire (25%) (Table 4). Across SPIBAs, 33% of loss was from fire and 67% loss was from anthropogenic drivers. Anthropogenic loss in dry eucalypt forest surpassed anthropogenic loss in wet eucalypt forest in recent years, although losses between these classes were equivalent over a twenty-two period (Fig. 6).

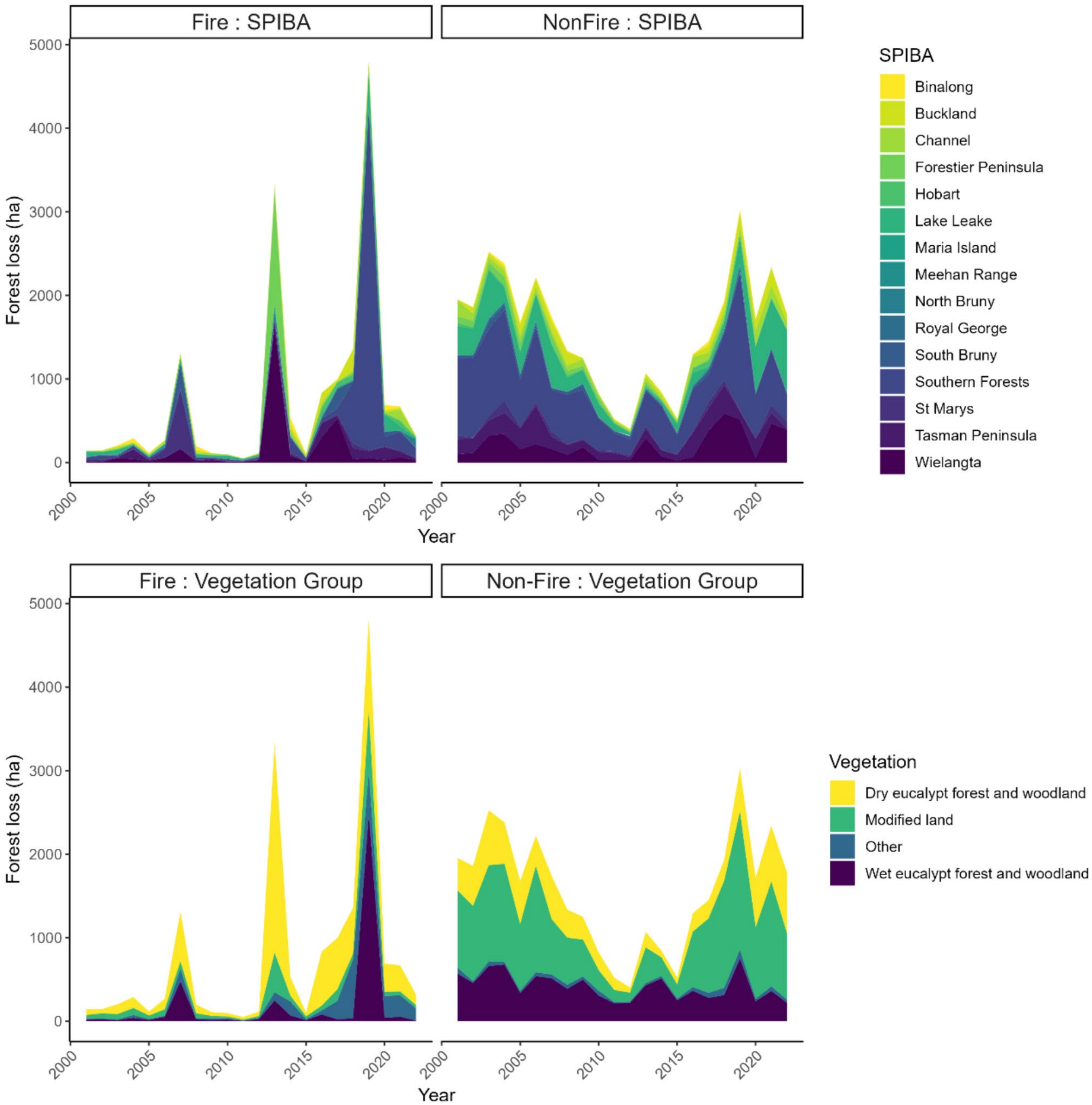

Fig. 6. Forest loss from fire and anthropogenic (non-fire) drivers by (**a**) Swift Parrot Important Breeding Areas (SPIBAs), and (**b**) Vegetation class between year 2000 to 2022.

Interrupted time-series analysis

Interrupted time series modelling revealed significant trends of anthropogenic forest loss within swift parrot important breeding areas (SPIBAs) pre- and post-forestry policy change (i.e. the *Forestry (Rebuilding the Forest Industry) Act 2014*). The change in forestry policy marked a distinct turning point in the trend of annual forest loss. Prior to the policy change, which occurred in 2014, the model identified a highly significant decreasing trend, with an estimated decrease of 139 hectares of forest loss per year between 2001 and 2013 ($p > 0.001$) (Fig. 7). There was a distinct shift in the trajectory after the *Forestry (Rebuilding the Forest Industry) Act 2014* was enacted, although this association was not immediately significant in the first year of change (Fig. 7). The post-interruption period, from 2015 onwards, demonstrated a highly significant increase in forest loss, amounting to an estimated 329 ha additional loss per year from 2015 onwards ($p > 0.001$). The rate of increase was more than double the rate of decrease prior to pre-policy change (Fig. 7), indicating a strong association between the change in forest policy and the observed trend. The interrupted time series analysis suggests that the 2014 policy change led to a notable and sustained rise in annual anthropogenic forest loss within SPIBAs.

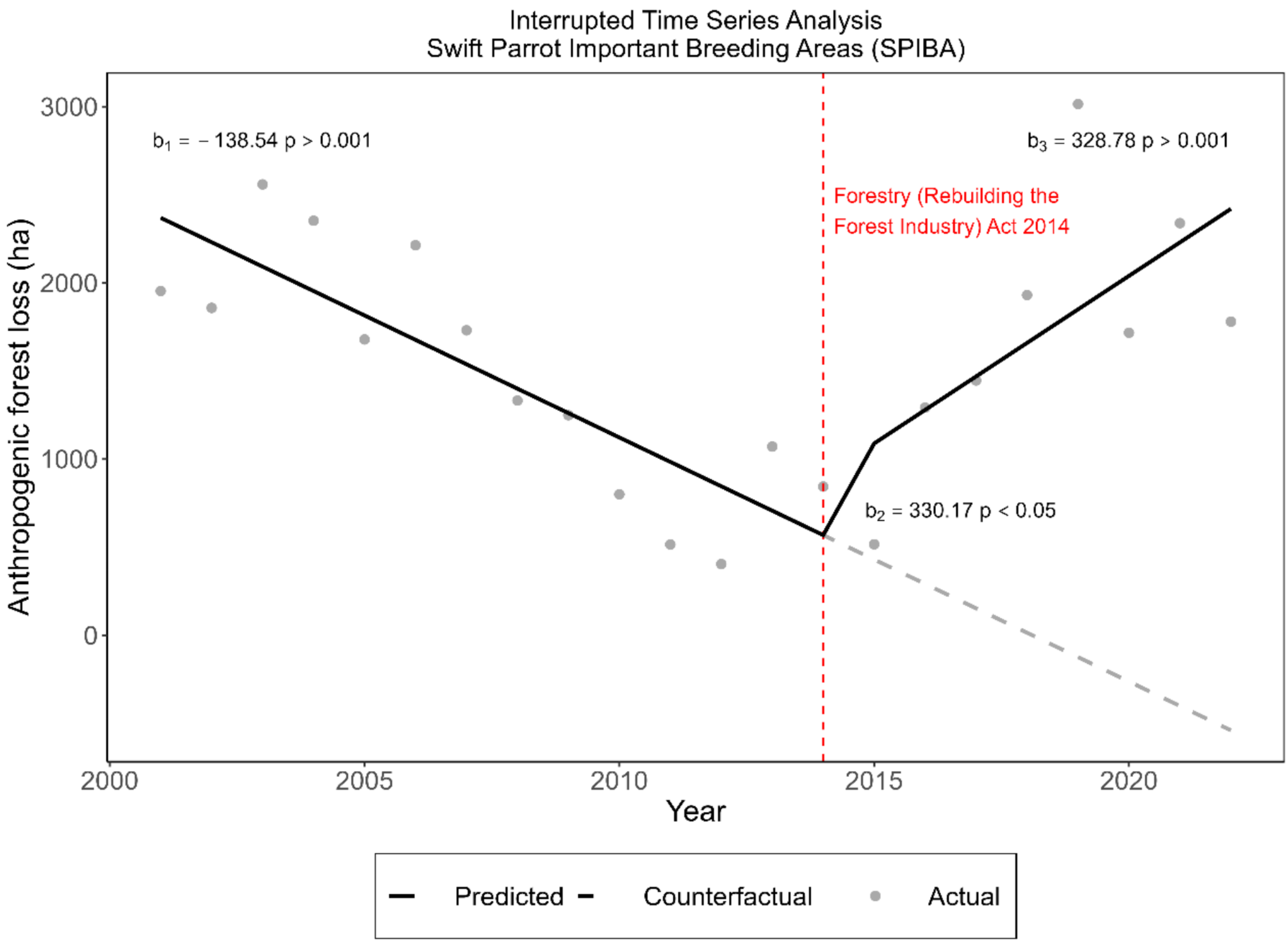

Fig. 7. Interrupted time-series of anthropogenic forest loss per year (2001–2022) in Swift Parrot Important Breeding Areas (SPIBAs) pre- and post- interruption (i.e. forest policy change); interruption: 2014. Solid lines represent model estimates of annual forest loss pre- and post- interruption. Forest loss was significantly negative prior to the interruption, showed a non-significant increase immediately afterwards (i.e. the first year) and increased significantly post-policy change. The dashed sloped line represents counterfactual model estimates of annual forest loss should the interruption not have taken place, based on preceding trends. The vertical dashed line indicates the year of the forest policy change in 2014. Grey points indicate actual anthropogenic forest loss per year.

Anthropogenic drivers

Our land-use and transition analysis of anthropogenic forest loss in SPIBAs identified human-drivers of forest degradation and loss. Production forestry was the prevailing driver of forest loss, followed by forestry on 'Conservation and natural environments' land and conversion of other land-uses to plantations (Figs. 4 and 8). A total of 57% of loss occurred on land that was, remained or transitioned to production forestry. We found that 27% of loss occurred on land that was, remained or transitioned to 'Conservation and natural environments' land (inclusive of secondary classes 'Nature conservation', 'Other minimal use' and 'Managed resource protection'). Accounting for overlap between these categories, forestry on these land classes accounted for 77% of all forest loss. Specifically, the original area that was retained as production forestry over the time interval accounted for 112km^2 of cleared forests between 2001–2022. The conversion of production forestry land to other land uses accounted for an additional 64km^2 of forest loss, whereas the conversion of conservation and plantation land to production forestry accounted for a further 18.3 km^2 of loss (Fig. 8).

Plantation land use doubled in forest areas that were cleared across the two decades, yet half of the original plantation area (17 km^2; 4.6% of loss) that was harvested was converted into other land uses (predominantly agriculture and production forestry of native forests) within that time, indicating limited permanence of plantations. However, the total cleared plantation land increased by 2021, as 88.4km^2 of other land uses were converted to plantation land uses (inclusive of 45.4 km^2 of production forestry land, 21.5km^2 of conservation land ('Other minimal use') and 21.5km^2 of agricultural land). Unconverted agricultural land accounted for 4% of forest loss (13.7km^2) across two decades and additional loss was incurred from transition to or from plantation or production forestry land uses. Conversion of agricultural and conservation ('Other minimal use') land to urbanization (residential and farm infrastructure) accounted for 10.6km^2 of anthropogenic forest loss, in addition to 1.9km^2 loss on pre-existing developed land (3.6%).

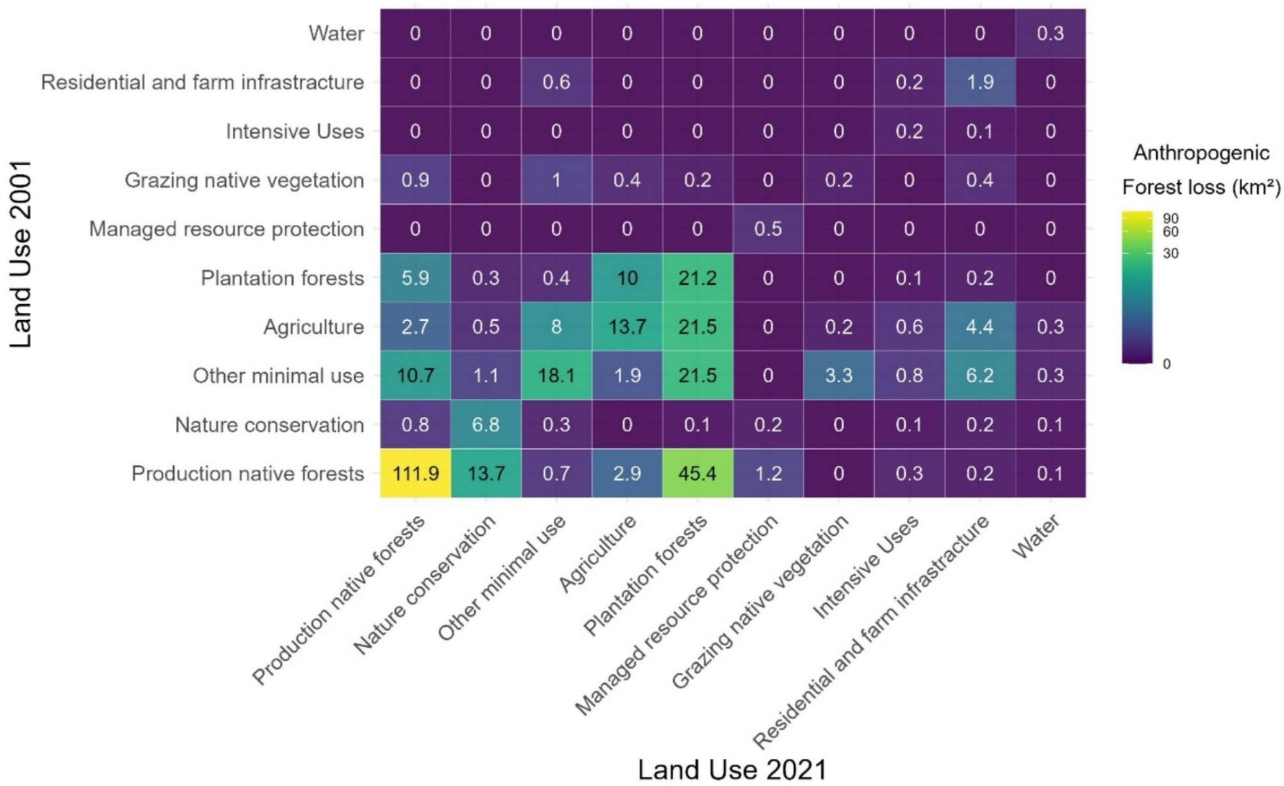

Fig. 8. Land-use change transition matrix (2001–2021) showing the area (km^2) of land use transition in areas impacted by anthropogenic forest loss (2001–2022) within swift parrot important breeding areas (SPIBAs). From left to right, values represent the area of land use transition within cleared forests between 2001 and 2021. Matching land uses indicate the area (km^2) of forest loss where the same land use category was recorded at both time points. Categories 'Nature conservation', 'Other minimal use' and 'Managed resource protection' are all sub-categories of ALUM primary class 'Conservation and Natural Environments'. Heatmap colour values are on a logarithmic (log1p) scale using R package *viridis 0.6.4*[56], to show the relative scale of small values. Grid numbers represent forest loss (km^2).

Discussion

Deforestation is a leading threat to biodiversity globally and thus is often a focal point of conservation programs. However, forest degradation, inclusive of stand-level disturbances and stand-replacement loss, can exert greater habitat and biodiversity loss at regional scales[11]. Substantial evidence now shows that forest degradation, together with deforestation, are the largest threats to forest ecosystems and forest-dependent species[15]. The swift parrot is subject to ongoing habitat loss and is among 20 Critically Endangered bird species the Australian Government has committed to save from extinction[37]. To evaluate whether human land-uses and policy are congruent with conservation goals, we quantified forest dynamics, trends and identified drivers of forest loss in the swift parrot breeding range.

Our results show a decline in swift parrot habitat extent and quality over the last two decades. This was caused by ongoing and escalating forestry practices, shifting land-use patterns, and the heightened prevalence of widespread fires. The extent of deforestation, disturbance and degradation impacted approximately a quarter of forests in the swift parrot's breeding range in 20 years. Over the same time period, the swift parrot population has declined from over 2100 birds to less than 500 birds[35]. We estimated little change in net forest area, indicating that contemporary habitat loss within the swift parrot breeding range is almost entirely forest degradation. Approximately 37% of eucalypt forests in the contemporary range boundaries were deforested historically, but the extent of historic degradation is likely to be far higher[20]. In combination with recent degradation and forest extent loss, and the limited extent of tall forests remaining, we estimate less than a quarter of habitat remains within contemporary range boundaries. Forest loss was decreasing in SPIBAs prior to forest policy change in the year 2014, after which forest loss increased at double the rate of the previous decrease. Even though fire extent and frequency increased between 2000 and 2022, fire accounted for only a quarter of forest loss in SPIBAs. Forestry was the dominant driver of forest loss, followed by other human-uses associated with timber harvesting.

Habitat loss has long been recognised as a key threat to the swift parrot[20,21,58–60] and recent research has confirmed that forest degradation amplifies the impact of other threats (i.e. nest site competition, nest predation)[25,61,62]. Forest extent loss (i.e. deforestation) was quantified within our study as loss of trees ≥ 5 m height in the year 2000 without replacement, whereas forest loss and disturbance (i.e. degradation) was equivalent to forests which experienced stand-replacement loss, height loss ≥ 50% or stand-replacing disturbances. We found extremely high levels of forest degradation across the swift parrot breeding range, and the extent of degradation was eight times that of deforestation within the years 2000–2020. For context, the percentage of forest extent loss, disturbance and degradation observed between 2000 and 2020 within the swift parrot's breeding range (22.2%) was about twice that observed in forests across Australia (9.3%) and the world (13.6%)[1]. This finding emphasises that regional estimates of forest change (i.e. state or national boundaries), which do not account for a species' range boundaries or reduction in forest quality, may under-estimate true impacts on species. Tasmania is a heavily forested state, with extensive forest cover outside the parrot's range, and overall achieved negative carbon emissions between 2011–2019[63]. However, our findings suggest a disparity between statewide forest extent and highly spatially concentrated forest degradation, disturbance and extent loss within the swift parrot's range. Accumulating evidence demonstrates that safeguarding intact landscapes from significant human impacts conserves biodiversity[11], but for much of the swift parrot's range this practice has not been implemented.

Fire-driven forest loss is characterised by temporary stand-disturbances and is a natural part of the regenerative cycle of *Eucalyptus* forest. Fire accounts for the majority of stand-disturbing forest loss in Australia (75%) relative to non-fire loss (25%)[6] but the exact opposite was true within the swift parrots breeding range, where anthropogenic drivers (75%) outweighed fire (25%). The impact of fire on the availability of key habitat resources, such as hollow-bearing or food trees, can be variable and temporary compared to timber harvesting. However, severe fires can lead to substantial declines in key habitat resources, exemplified by a 62.8% loss of nesting cavities and 48.6% of trees in a single breeding area after a 2014 fire[64]. Moreover, numerous *Eucalyptus* species, even those considered fire-tolerant, cannot survive frequent fires[65]. In SPIBAs, forest loss from fire (25–33%) was comparatively much lower than in forests across Australia (75%)[6], but fire frequency aligned with the nationwide trend, notably during the 2019 bushfires. With growing fire frequency and intensity due to global warming[17,18], and the heightened flammability of regenerating forests, forest quality and intactness[9] are likely to decrease further.

Swift parrots often nest in forests that are within the boundaries of areas designated for timber harvesting. Since the introduction of the *Forestry (Rebuilding the Forest Industry) Act* (2014)[44], anthropogenic forest loss within SPIBAS has significantly escalated. Although the swift parrot is Critically Endangered[34], targeted habitat protection is compromised by regional forest agreements that take legal precedence over other environmental laws. SPIBAs lack formal protection and fall under provisional guidelines, while unsustainable forest practices further threaten the swift parrot's survival. Our analysis shows that not only is forestry ongoing, but that it is increasing in critical remnant swift parrot habitat.

Anthropogenic forest degradation occurred predominantly in production forestry areas and occurred to a lesser degree in areas managed as 'Conservation and natural environments.' Within the 'Conservation and natural environments' class are secondary land uses, some of which permit timber harvesting. Concerningly, anthropogenic forest loss also occurred on lands that prohibit harvesting ('Nature conservation'; 6.8km^2). This may be attributed to illicit firewood collection, but this is challenging to identify without spatially explicit harvest and permit data. Interestingly, native forests and conservation areas in the year 2000 account for most of the plantation area today, and this transition was the second largest driver of forest loss. On current vegetation maps, native forests converted to plantations are classed 'modified land'. We found that this significant habitat loss may be overlooked if habitat assessments are restrained to contemporary vegetation mapping of eucalypt forest. Of note, little over half of the original plantations in the year 2000 that were cleared were retained as plantations, suggesting short-lived management of plantation forests as a perpetual resource for forest-products, and a reliance on clearing intact native forests to create new plantations.

Degradation may be overlooked or unreported when considering contemporary habitat availability, as well as time lags in extinction debt incurred from historic degradation[66] and future management for threatened species. The term "degradation" has been defined and measured in various ways in global forest literature, often extending beyond stand and tree size dynamics to incorporate metrics such as edge effects, landscape connectivity, and industrial pressures[13,67]. These broader definitions are vital for assessing biodiversity impacts, particularly for forest-dependent species[14,15,68]. Global datasets like the Forest Landscape Integrity Index (FLII) (Grantham et al., 2020), which has previously demonstrated the importance of high integrity forest for swift parrot nest survival[25], and the Forest Structural Condition or Integrity Index (FSCI/FSII)[69] incorporate such factors but are temporally static. The GLCLUC dataset used in this study offers the best available temporal data on forest degradation, disturbance and loss since 2000, though its definition is limited to forest stand and height changes[1]. Our estimate of degraded and disturbed forests in the breeding range (22.2%/ 20 years) likely underestimates the true extent by omitting other indicators of forest integrity, such as connectivity and edge effects. To meet global targets (i.e., the Kunming-Montreal Global Biodiversity Framework), future tracking of forest degradation will benefit from nuanced temporal global datasets that account for a broad range of indicators[67,70].

Delineating the drivers of forest degradation also presents numerous challenges in areas of temporally consistent forest cover. Although remote sensing technology has proven capacity to detect land-use changes associated with deforestation[7], detecting drivers of degradation is more challenging. In our study, land-use maps between 2001 and 2021 illustrated the conversion of past land uses to those recognised today. We show that these data sources provide a useful indication of the underlying drivers when forest cover was largely unchanged, but had undergone loss from anthropogenic causes. Multiple studies recognize the link between land cover and land use as a key challenge in monitoring, modelling, and communicating land changes[71,72]. Moreover, human-driven changes in land use are a significant driver of biodiversity decline and are predicted to worsen in the coming century[73]. Increased spatial capacity to detect forest degradation and its causes are continually evolving, which will enhance the transparency of human land-use impacts into the future.

Our study has broader significance for other forest species and communities. There have been recent efforts to estimate habitat loss for Australia's threatened species based on tree cover change[74,75] but our study indicates these are likely to be underestimates as they exclude forest degradation. As the swift parrots' range covers much of the remaining *Eucalyptus* forest in the east and north of Tasmania, our analysis of historic deforestation, as well as contemporary forest loss and degradation, points to the substantial habitat loss experienced by many other co-occurring forest species, inclusive of birds, mammals, invertebrates, plants, and *Eucalyptus* vegetation communities.

This analysis was a result of free, publicly available datasets, cloud-processing platforms for large raster datasets and coding and statistical software. Our results provide transparent accounts of deforestation, degradation, and forest loss disaggregated by drivers, both natural and human driven. We show that current thematic maps may not reflect the legacy of past disturbance even within two decades. Reliance on these data sources to report habitat management for forest-specialists like swift parrots do not account for past habitat disturbance, shifting land-use patterns, and policy changes. Our study contains some data limitations and necessary assumptions. Our analysis of past trends is constrained to the year 2000 due to the availability of satellite data, meaning historical degradation is difficult to quantify despite its known severity[20,58]. Our study assumes that non-fire forest loss is anthropogenic, and we acknowledge that trees may suffer mortality and collapse from other natural drivers (e.g. wind, drought, salinity, pathogens, defoliation). Nevertheless, there is little documented evidence for these effects in Tasmania in undisturbed forests, and the contribution of natural mortality other than fire is considered negligible. The true extent of tree heights is not completely represented by the forest strata data, due to pixel saturation at tall heights within the dataset, but it does provide the most detailed temporal spatial information of forest regeneration, afforestation and deforestation. Our estimates of forest degradation are conservative, as we do not include all indicators of degradation and disturbance, due to spatial dataset limitations. Finally, our estimates of historic deforestation are conservative as we apply current range boundaries, but the swift parrot's past distribution was likely greater than it is today.

Forest degradation can have greater impacts than deforestation on retaining biodiversity at scales important for the persistence of species. As projected climate change and increased fire frequencies are expected to further degrade forests, addressing degradation from human land-uses in forested areas is a clear and important path towards securing habitat for biodiversity. Where policies and land-use practices are not aligned with species conservation, spatial products, which are increasingly detailed, can provide transparent accounts of forest change and provide direction for improved land management. The swift parrot exemplifies the challenges of quantifying habitat loss for threatened species in degraded forests, especially following policy change and land-use transitions. For the swift parrot to have a chance at averting extinction, forestry practices and land policy need to change to appropriately conserve intact forests for the perpetuity of the swift parrot.

Data availability

Spatial datasets used in this study are accessible from the sources cited in Methods and Table S1 (Supporting Information). Estimation of forest degradation, disturbance and forest loss was done in Google Earth Engine. Example javascript code and forest loss tutorial available on the Google Earth Engine Community website at https://developers.google.com/earth-engine/tutorials/community/forest-cover-loss-estimation.

Received: 31 July 2024; Accepted: 26 February 2025
Published online: 12 March 2025

References

1. Potapov, P. et al. The global 2000–2020 land cover and land use change dataset derived from the Landsat archive: first results. *Front. Remote Sens.* **3**, 856903. https://doi.org/10.3389/frsen.2022.856903 (2022).
2. Thompson, I. D. et al. An operational framework for defining and monitoring forest degradation. *Ecol. Soc.* **18** (2013).
3. Vásquez-Grandón, A., J., P., Donoso & Gerding, V. Forest degradation: when is a forest degraded? *Forests* **9** https://doi.org/10.3390/f9110726 (2018).
4. Potapov, P. et al. Mapping global forest canopy height through integration of GEDI and Landsat data. *Remote Sens. Environ.* **253**, 112165. https://doi.org/10.1016/j.rse.2020.112165 (2021).
5. Hansen, M. C. et al. High-resolution global maps of 21st-century forest cover change. *Science* **342**, 850–853. https://doi.org/10.1126/science.1244693 (2013).
6. Tyukavina, A. et al. Global trends of forest loss due to fire from 2001 to 2019. *Front. Remote Sens.* **3** (2022).
7. Curtis, P. G., Slay, C. M., Harris, N. L., Tyukavina, A. & Hansen, M. C. Classifying drivers of global forest loss. *Sci. (American Association Advancement Science).* **361**, 1108–1111. https://doi.org/10.1126/science.aau3445 (2018).
8. Kadoya, T., Takeuchi, Y., Shinoda, Y. & Nansai, K. Shifting agriculture is the dominant driver of forest disturbance in threatened forest species' ranges. *Commun. Earth Environ.* **3**, 108. https://doi.org/10.1038/s43247-022-00434-5 (2022).
9. Ma, J., Li, J., Wu, W. & Liu, J. Global forest fragmentation change from 2000 to 2020. *Nat. Commun.* **14**, 3752. https://doi.org/10.1038/s41467-023-39221-x (2023).
10. Li, W. et al. Human fingerprint on structural density of forests globally. *Nat. Sustain.* **6**, 368–379. https://doi.org/10.1038/s41893-022-01020-5 (2023).
11. Barlow, J. et al. Anthropogenic disturbance in tropical forests can double biodiversity loss from deforestation. *Nature* **535**, 144–147. https://doi.org/10.1038/nature18326 (2016).
12. Ghazoul, J., Burivalova, Z., Garcia-Ulloa, J. & King, L. A. Conceptualizing forest degradation. *Trends Ecol. Evol.* **30**, 622–632. https://doi.org/10.1016/j.tree.2015.08.001 (2015).
13. Grantham, H. S. et al. Anthropogenic modification of forests means only 40% of remaining forests have high ecosystem integrity. *Nat. Commun.* **11**, 5978–5978. https://doi.org/10.1038/s41467-020-19493-3 (2020).
14. B Lindenmayer, D. Forest biodiversity declines and extinctions linked with forest degradation: A case study from Australian tall, wet forests. *Land* **12**, 528. https://doi.org/10.3390/land12030528 (2023).
15. Betts, M. G. et al. Global forest loss disproportionately erodes biodiversity in intact landscapes. *Nature* **547**, 441–444. https://doi.org/10.1038/nature23285 (2017).
16. Olah, G. et al. Ecological and socio-economic factors affecting extinction risk in parrots. *Biodivers. Conserv.* **25**, 205–223. https://doi.org/10.1007/s10531-015-1036-z (2016).
17. Asamoah, E. F., Beaumont, L. J. & Maina, J. M. Climate and land-use changes reduce the benefits of terrestrial protected areas. *Nat. Clim. Change.* **11**, 1105–1110. https://doi.org/10.1038/s41558-021-01223-2 (2021).

18. Powlen, K. A., Salerno, J., Jones, K. W. & Gavin, M. C. Identifying socioeconomic and biophysical factors driving forest loss in protected areas. *Conserv. Biol.* **37**, e14058. https://doi.org/10.1111/cobi.14058 (2023).
19. Gibbons, P. & Lindenmayer, D. *Tree Hollows and Wildlife Conservation in Australia* (CSIRO publishing, 2002).
20. Saunders, D. & Russell, T. Settlement and swift parrots - Historic and ongoing habitat loss for a critically endangered species (1788–2016). *Papers Proc. - Royal Soc. Tasmania* **150** https://doi.org/10.26749/rstpp.150.2.55 (2016).
21. Webb, M. H., Stojanovic, D. & Heinsohn, R. Policy failure and conservation paralysis for the critically endangered swift parrot. *Pac. Conserv. Biol.* **25**, 116. https://doi.org/10.1071/PC18020 (2019).
22. Webb, M. H. et al. Location matters: using spatially explicit occupancy models to predict the distribution of the highly mobile, endangered swift parrot. *Biol. Conserv.* **176**, 99–108. https://doi.org/10.1016/j.biocon.2014.05.017 (2014).
23. Stojanovic, D., Rayner, L., Webb, M. & Heinsohn, R. Effect of nest cavity morphology on reproductive success of a critically endangered bird. *Emu - Austral Ornithol.* **117**, 247–253. https://doi.org/10.1080/01584197.2017.1311221 (2017).
24. Stojanovic, D., Webb, M., Roshier, D., Saunders, D. & Heinsohn, R. Ground-based survey methods both overestimate and underestimate the abundance of suitable tree-cavities for the endangered swift parrot. *Emu - Austral Ornithol.* **112**, 350–356. https://doi.org/10.1071/MU11076 (2012).
25. Owens, G., Heinsohn, R., Crates, R. & Stojanovic, D. Long-term ecological data confirm and refine conservation assessment of critically endangered swift parrots. *Anim. Conserv.* **26**, 450–463. https://doi.org/10.1111/acv.12834 (2023).
26. Porfirio, L. L., Harris, R. M. B., Stojanovic, D., Webb, M. H. & Mackey, B. Projected direct and indirect effects of climate change on the swift parrot, an endangered migratory species. *Emu - Austral Ornithol.* **116**, 273–283. https://doi.org/10.1071/MU15094 (2016).
27. Brereton, R., Mallick, S. A. & Kennedy, S. J. Foraging preferences of swift parrots on Tasmanian Blue-gum: tree size, flowering frequency and flowering intensity. *Emu - Austral Ornithol.* **104**, 377–383 (2004).
28. Department of State Growth. *Tasmania's Forest Management System: an Overview (2021 update)* (Tasmanian Government, 2021).
29. Koch, A. & Munks, S. A proposed strategy for maintaining mature forest habitat in Tasmania's wood production forests. *Ecol. Manag Restor.* **19**, 239–246. https://doi.org/10.1111/emr.12337 (2018).
30. Koch, A. J., Webb, M., Cawthen, L., Livingston, D. & Munks, S. A. Managing mature forest features: the production, accuracy and ecological relevance of a landscape-scale map. *Ecol. Manag Restor.* **19**, 247–256. https://doi.org/10.1111/emr.12336 (2018).
31. Stojanovic, D. et al. Validation of a landscape-scale planning tool for cavity-dependent wildlife. *Austral Ecol.* **39**, 579–586. https://doi.org/10.1111/aec.12118 (2014).
32. Forest Practices Authority. *Interim Species Habitat Planning Guideline for the conservation management of Lathamus discolor (swift parrot) in areas regulated under the Tasmanian forest practices system* (Forest Practices Authority, 2010).
33. Heinsohn, R. et al. A severe predator-induced population decline predicted for endangered, migratory swift parrots (Lathamus discolor). *Biol. Conserv.* **186**, 75–82. https://doi.org/10.1016/j.biocon.2015.03.006 (2015).
34. Commonwealth of Australia. EPBC Act List of Threatened Fauna. *Species Profile and Threats Database, Department of the Environment, Canberra*. https://www.environment.gov.au/sprat (2021).
35. Olah, G., Waples, R. S. & Stojanovic, D. Influence of molecular marker type on estimating effective population size and other genetic parameters in a critically endangered parrot. *Ecol. Evol.* **14**, e11102. https://doi.org/10.1002/ece3.11102 (2024).
36. DAWE. The Australian Government's Threatened Species Strategy 2021–2031. Department of Agriculture, Water and the Environment, Canberra, April (2021).
37. DCCEEW. Threatened Species Strategy Action Plan 2022–2032. Canberra, September (2022).
38. DAWE. Threatened Species Strategy Action Plan 2021–2026. Department of Agriculture, Water and the Environment, Canberra, February (2022).
39. United Nations Climate Change Conference of the Parties. Glasgow Leaders' Declaration on Forests and Land Use (2021).
40. Commonwealth of Australia. National Recovery Plan for the Swift Parrot (Lathamus discolor) (2019).
41. Saunders, D. & Tzaros, C. National Recovery Plan for the Swift Parrot Lathamus discolor, Birds Australia, Melbourne (2011).
42. Michaels, K., Norton, T., Lacey, M. & Williams, J. Spatial analysis of Tasmania's native vegetation cover and potential implications for biodiversity conservation. *Ecol. Manag Restor.* **11**, 194–200. https://doi.org/10.1111/j.1442-8903.2010.00549.x (2010).
43. Keogh, V., Ward, M., Stewart, R., Blanch, S. & Cronin, T. WWF Trees Scorecard 2023 Technical Report. WWF-Australia, Sydney, (2023).
44. *Forestry (Rebuilding the Forest Industry) Act 2014.* Tasmania, (2014).
45. Sustainable Timber Tasmania. Annual Report 2023. Tasmania, (2023).
46. Boland, D. J. et al. *Forest Trees of Australia* 5th edn (CSIRO Publishing, 2006).
47. NRE. *Tasmanian Land Use 2021* (Department of Natural Resources and Environment, 2021).
48. DPIPWE. *Tasmanian Land Use 2001* (Department of Primary Industries, Parks, Water and Environment, 2003).
49. ABARES. *Guidelines for Land Use Mapping in Australia: Principles, Procedures and Definitions*, fourth edition (Australian Bureau of Agricultural and Resource Economics and Sciences, 2011).
50. Pebesma, E. & Bivand, R. *Spatial Data Science: With applications in R* (2023).
51. Pebesma, E. Simple features for R: standardized support for spatial vector data. *R J.* **10**, 439–446. https://doi.org/10.32614/RJ-2018-009 (2018).
52. R: A language and environment for statistical computing (R Foundation for Statistical Computing, 2023).
53. DCCEEW. *Australia - Present Major Vegetation Groups - NVIS Version 6.0 (Albers 100m Analysis product)* (Department of Climate Change, Energy, the Environment & Water, 2023).
54. DCCEEW. *Australia - Pre-1750 Major Vegetation Groups - NVIS Version 6.0 (Albers 100m Analysis product)* (Department of Climate Change, Energy, the Environment & Water, 2023).
55. Tennekes, M. Thematic maps in R. *J. Stat. Softw.* **84**, 1–39. https://doi.org/10.18637/jss.v084.i06 (2018).
56. viridis(Lite) - Colorblind-Friendly Color Maps for R v. 0.6.4. (2023).
57. McDowall, D., McCleary, R. & Bartos, B. J. *Interrupted Time Series Analysis* (Oxford University Press, 2021).
58. Allchin, R., Kirkpatrick, J. & Kriwoken, L. On not protecting the parrot: impact of conservation and planning legislation on an endangered species in Tasmania. *J. Int. Wildl. Law Policy*. **16**, 81–104. https://doi.org/10.1080/13880292.2013.764777 (2013).
59. Brown, P. B. *The Swift Parrot Lathamus discolor White: A report on its ecology, distribution and status, including management considerations* (Department of Lands, Parks and Wildlife, 1989).
60. Swift Parrot Recovery Team. *Swift Parrot Recovery Plan* (Department of Primary Industries Water and Environment, 2001).
61. Stojanovic, D., Owens, G., Young, C., Alves, F. & Heinsohn, R. Do nest boxes breed the target species or its competitors? A case study of a critically endangered bird. *Restor. Ecol.* **29**, e13319. https://doi.org/10.1111/rec.13319 (2020).
62. Stojanovic, D. et al. Discovery of a novel predator reveals extreme but highly variable mortality for an endangered migratory bird. *Divers. Distrib.* **20**, 1200–1207. https://doi.org/10.1111/ddi.12214 (2014).
63. Mackey, B., Moomaw, W., Lindenmayer, D. & Keith, H. Net carbon accounting and reporting are a barrier to understanding the mitigation value of forest protection in developed countries. *Environ. Res. Lett.* **17**, 54028. https://doi.org/10.1088/1748-9326/ac661b (2022).
64. Stojanovic, D., Webb nee Voogdt, J., Webb, M., Cook, H. & Heinsohn, R. Loss of habitat for a secondary cavity nesting bird after wildfire. *Ecol. Manage.* **360**, 235–241. https://doi.org/10.1016/j.foreco.2015.10.040 (2016).
65. Fairman, T. A., Bennett, L. T. & Nitschke, C. R. Short-interval wildfires increase likelihood of resprouting failure in fire-tolerant trees. *J. Environ. Manage.* **231**, 59–65. https://doi.org/10.1016/j.jenvman.2018.10.021 (2019).

66. Kuussaari, M. et al. Extinction debt: a challenge for biodiversity conservation. *Trends Ecol. Evol.* **24**, 564–571 (2009).
67. Hansen, A. J. et al. A policy-driven framework for conserving the best of Earth's remaining moist tropical forests. *Nat. Ecol. Evol.* **4**, 1377–1384. https://doi.org/10.1038/s41559-020-1274-7 (2020).
68. Pillay, R. et al. Humid tropical vertebrates are at lower risk of extinction and population decline in forests with higher structural integrity. *Nat. Ecol. Evol.* **6**, 1840–1849. https://doi.org/10.1038/s41559-022-01915-8 (2022).
69. Hansen, A. et al. Global humid tropics forest structural condition and forest structural integrity maps. *Sci. Data*. **6**, 232. https://doi.org/10.1038/s41597-019-0214-3 (2019).
70. Pillay, R. et al. The Kunming-Montreal Global Biodiversity Framework needs headline indicators that can actually monitor forest integrity. *Environ. Res. Ecol.* https://doi.org/10.1088/2752-664X/ad7961 (2024).
71. Comber, A. J. The separation of land cover from land use using data primitives. *J. Land. Use Sci.* **3**, 215–229 (2008).
72. Verburg, P. H., Neumann, K. & Nol, L. Challenges in using land use and land cover data for global change studies. *Glob Change Biol.* **17**, 974–989. https://doi.org/10.1111/j.1365-2486.2010.02307.x (2011).
73. Powers, R. P. & Jetz, W. Global habitat loss and extinction risk of terrestrial vertebrates under future land-use-change scenarios. *Nat. Clim. Change.* **9**, 323–329. https://doi.org/10.1038/s41558-019-0406-z (2019).
74. Ward, M. S. et al. Lots of loss with little scrutiny: the attrition of habitat critical for threatened species in Australia. *Conserv. Sci. Pract.* **1**, e117. https://doi.org/10.1111/csp2.117 (2019).
75. Simmonds, J. S., Watson, J. E. M., Salazar, A. & Maron, M. A composite measure of habitat loss for entire assemblages of species. *Conserv. Biol.* **33**, 1438–1447. https://doi.org/10.1111/cobi.13331 (2019).

Acknowledgements

We acknowledge the traditional owners of lutrawita (Tasmania), the Palawa/Pakana people, who are the traditional custodians of the forests where the swift parrot breeds. This research was supported by the Holsworth Endowment Fund provided by the Ecological Society of Australia on behalf of Dr. Bill Holsworth and the Australian Government Department of Agriculture, Water and the Environment, via NRM South. We would like to thank the Swift Parrot Recovery Team for consultation at the outset of this project. The authors have no conflict of interest to declare.

Author contributions

GO and DS conceptualized the study; GO undertook the study design, analysis, visualization and writing of the original manuscript; PG, RH and DS provided supervision and contributed to critical redrafting of the manuscript; All authors read and approved the final manuscript.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1038/s41598-025-92231-1.

Correspondence and requests for materials should be addressed to G.O.

Reprints and permissions information is available at www.nature.com/reprints.

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.