Ecosystem transformation following the mid-nineteenth century cessation of Aboriginal fire management in Cape Pillar, Tasmania

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Abstract
Ongoing European suppression of Aboriginal cultural land management since early-nineteenth century colonisation is widely thought to have caused major transformations across all Australian landscapes, including vegetation thickening, severe fires and biodiversity declines. However, these effects are often confounded in the densely settled southern Australia due to European land transformation. Landscapes currently under conservation and national park management in Tasmania are generally less disturbed, providing an opportunity to track ecosystem changes caused by the removal of Aboriginal peoples following colonisation in southern Australia. We use a multi-proxy palaeoecological technique and the analysis of historical aerial photography to investigate these changes in Cape Pillar, southeast Tasmania. Results reveal a major ecological shift following European colonisation, with the replacement of stable, open wet heathland characterised by minor fires (active cultural land use) with dense dry scrub characterised by major fires (cessation of cultural land use). We also discuss potential background role of regional climatic shifts in the observed ecological changes. Management programmes designed to restore open heathland pre-colonial cultural ecosystem would help reduce the risk of large fires in Cape Pillar.

Keywords Cape Pillar · Cultural burning · European colonisation · Fire · Heathland · Indigenous land use · Three Capes Track

Introduction
Indigenous people have sustainably interacted with the Australian landscape for many millennia, and this interaction yielded the culturally diverse landscapes that we see today in Australia (Ens et al. 2017). The disruption of indigenous people–landscape interaction by European settlement commencing in the late eighteenth century led to major changes in the Australian environment, including changes in vegetation and fire regimes (Kirkpatrick 1994; Bowman 1998; Hallam 2014). Indigenous people used frequent small-scale fires to maintain open vegetation (less woody biomass load and connectivity) in the past to increase resource availability (e.g. maintaining hunting grounds, freshwater sources, and edible plant foods) and mitigate against catastrophic wildfires, consequentially promoting biodiversity (Bowman 1998; Ens et al. 2017; Gammage 2008, 2011; Adeleye et al. 2021a). The removal of indigenous people and the suppression of their cultural land management following European invasion resulted in major transformations across most Australian landscapes, involving the loss of biodiversity, increased soil erosion due to land clearance and agricultural activities and an increase in the occurrence of large fires (Mariani et al. 2022; Bui et al. 2010; Woinarski et al. 2015; Adeleye et al. 2021b; Moss et al. 2016). This shift in fire regime was often associated with increased woody biomass accumulation and connectivity (woody thickening). This is particularly evident in southeast Australia, which is characterised by flammable vegetation types, with increased occurrence of destructive wildfires in the recent decades (Mariani et al. 2022; Adeleye et al. 2021b).
In southeast mainland Australia, historical records and palaeoecological proxies point to a shift from open, patchy, grassy woodland under indigenous management to denser woody vegetation that facilitated the spread of large wildfires, especially since the 1850s (Mariani et al. 2022; Adel-eye et al. 2021b). In northwest Tasmania, the forced removal of indigenous people by Europeans led to forest encroachment in grasslands previously maintained by indigenous people in the area (Bowman et al. 2013; Fletcher et al. 2021). Vegetation thickening in treeless areas has been associated with severe fires in Tasmania today (Marsden-Smedley 2009; Foulkes et al. 2021) and loss of native plant species diversity (Bargmann and Kirkpatrick 2015). It is important to acknowledge that changes in fire regime that followed European invasion are confounded by other ecological changes associated with natural resources exploitation such as forestry, grazing and land clearance for agriculture and mining that often involved setting landscape fires (Harle et al. 2002; Romanin et al. 2016; Moss et al. 2016). In order to fully understand the spatial extent of the impact of European-driven land-use change on the Tasmanian landscape, we require additional centennial-scale vegetation and fire history studies from landscapes less affected by European-driven anthropogenic disturbances.

In this study, our goal is to understand pre- and post-colonial environmental trajectories in a southeast Tasmanian site (Cape Pillar, Tasman Peninsula). The Cape Pillar is remote, fringed with towering 300-m sea cliffs, unaffected by colonial natural resource exploitation and conserved as a national park (Fig. 1). Archaeological surveys suggest the region was frequently used by the Tasmanian Aborigines (Jones et al. 2019), likely for hunting seal colonies that are common at the base of sea cliffs. The visit to Cape Pillar by European James Calder in 1848, as part of his Tasman Peninsula survey, indicates a relatively easy access to the cape (Calder 1985). He describes generally open vegetation on the Cape at this time, composed of open eucalypt forests, thickets and short heaths, with belts of dense scrub (see Appendix S1 for Calder’s detailed note on his visit to Cape Pillar). However, in mid 1960s, access to Cathedral Bluff, at the terminus of Cape Pillar, proved extraordinarily difficult, requiring multiple attempts of an exploratory party given the impenetrable vegetation (Christie 1970; see Appendix S2 for detailed accounts of several attempts to reach Cape Pillar in the 1960s). Whilst climate change likely has influenced centennial to millennial-scale ecosystem changes in Cape Pillar, we hypothesise that the cause of the dense vegetation apparent in the 1960s was related to the cessation of frequent, skilful Aboriginal fire management that facilitated the route of Calder. Specifically, we aim to investigate vegetation, wetlands and fire-regime changes associated with European settlement and the removal of indigenous people in the area and identify the potential influence of regional climate on these changes.

Cape Pillar has now become a major tourist attraction following the establishment of the “Three Capes Track” in the Tasman National Park (Ellice-Flint 2017) that has cut a route through the thick scrub and forests. Results from this study will not only contribute to the understanding of European transformation of the Tasmanian landscape but will also help refine fire management to both protect biodiversity

Fig. 1  a, b Cape Pillar landscape, showing the plateau with lichen and wind-edaphic limited heath vegetation in the foreground that was burned in 1979–1980 (photos by Simon Haberle). c Allocasuarina littoralis forest with scrub and coastal heathland complex forming dense vegetation across the Cape Pillar plateau. d The impact of recent wind-storm disturbance on the Allocasuarina littoralis forest with scrub and coastal heathland complex. The 1979–1980 fire may have created greater exposure of dense forest and shrub vegetation to windthrow events.
through targets ecological restoration and protect tourists from uncontrolled bushfires.

**Methods**

**Study area: Tasman Peninsula and Cape Pillar**

Cape Pillar is one of three capes that protrudes into the Southern Ocean from the Tasman Peninsula. The Tasman Peninsula has an area of about 473 km² and a coastline of about 323 km long. The surface geology of the peninsula is mainly composed of Jurassic dolerites in addition to Triassic and Permian mudstones and sandstones (Banks et al. 1989; Cullen and Dell 2011). Cape Pillar geology is mainly characterised by Jurassic dolerites, whilst Permian glaciomarine sediments (mudstone and sandstones) are limited to the coastal strip, and Quaternary deposits are restricted to only few sites. Pliocene—Pleistocene-aged cliffs, of up to 300 m asl, rim the Cape (Cullen and Dell 2011), formed as a result of both periglacial erosion during ice-ages and coastal erosion during interglacials (Cullen and Dell 2011; Leaman 1999). The surface of the Cape Pillar is capped by extensive Pleistocene dune systems, the highest coastal aeolian landforms in Australia (Cullen and Dell 2011).

The Tasman Peninsula climate is typical of a temperate oceanic climate with mild temperatures, and Southern Westerly (SW) winds largely modulate cold front passage in the area, which brings high precipitation (750–1000 mm) throughout the year, especially during winter (Cullen and Dell 2011; Department of Primary Industries, Water and Environment 2012). The SW wind–driven winter rainfall has declined at least in the last 20 years (associated with the increased intensity of the Southern Annular Mode (SAM) positive phase) due to southward shifts in SW winds positions, which is associated with ozone depletion, rising atmospheric CO₂ and rising temperatures in Australia (Australian Bureau of Meteorology 2013).

Vegetation in the Tasman Peninsula consists of wet and dry sclerophyll forests, coastal heathland and scrub with rainforests occurring in a few moist gullies and mountain tops (Figs. 1 and 2). Specifically, Cape Pillar vegetation is dominated by coastal heathland, scrub and Allocasuarina littoralis and eucalypt forest (Fig. 2). The interplay of climate, fire regime, topography and biotic factors determines the structure, composition and distribution of vegetation. For example, dry sclerophyll forests grade into wet forests with increasing site moisture, and forests grade into heathland with increasing site exposure to salt spray and wind damage. On a finer scale, soil drainage and substrate geology also influence plant composition within vegetation types (Brown and Duncan 1989; Cullen and Dell 2011). The plant communities have sharp contrasting flammability levels, with heath most flammable and rainforest the least which affect fire-return intervals (Jackson 1968a, 1968b). In 2013, extremely intense fire occurred on the adjoining Forrestier Peninsula, in part driven by heavy fuel load in long unburned dry sclerophyll forests (Ndalila et al. 2018).

Recent Tasmanian archaeological geospatial modelling has identified the Tasman Peninsula area as one of the most...
suitable occupation sites for indigenous people in the past, due to the coastal nature and open, dry landscape (Fig. 2; Jones et al. 2019). Ethnographical accounts also indicate that indigenous people were actively present in the area until European settlement, and some of the indigenous activities recorded include shell fishing and hunting macropods and seals, as well as landscape fire for hunting and habitat management (Fig. 2; Jones 1971). European arrival in the Tasman Peninsula (Risdon Cove) commenced in 1803 AD, with settlement in Premaydena (Port Arthur) by 1830 AD, a penitentiary for British convicts that closed in 1853. Today, the convict site is listed as a World Heritage historic site (UNESCO Word Heritage Convention 2007). Agricultural development and forestry occurred in the area surrounding Port Arthur and the hinterlands of Tasman Peninsula, but Cape Pillar was unaffected given the poor soils, rugged coastline and limited timber resources.

**Coring sites**

Sediment cores were obtained from four shallow (<1 m) wetlands on Cape Pillar: Copping’s Swamp (CS), Teddy’s Pond (TP), Perdition Pond (PP) and Snake Head Pond (SHP).

CS (43°12′45.95″S, 147°58′23.10″E; 315 m asl; core depth = 60 cm) is a hanging peat swamp adjacent to the Three Capes walking track and is dominated by wet heathland communities, with dense grass and Leptospermum thickets. TP (43°12′42.74″S, 147°57′48.10″E, 295 m asl, core depth = 16.5 cm) is an open water site surrounded by Allocasuarina littoralis woodland, with a mosaic of wet heathland and extensive area of wind-pruned stunted wet Eucalyptus stands. PP (43°12′58.33″S, 147°58′43.08″E; 275 m asl; core depth = 38 cm) is an ephemeral pond in a deflated dune swale surrounded by coastal heathland communities that were burned 1979/1980. Evidence of recreational camping sites and associated campfires was evident around the pond. SHP (43°13′0.48″S, 147°58′55.08″E; 300 m asl; core depth = 17 cm) is an open water site surrounded by Allocasuarina littoralis woodland and coastal heathland communities and located close to the Three Capes Track (Fig. 1).

**Core analysis**

Sediment core lithologies were described and chronology was developed for the longest core (CS) based on $^{210}\text{Pb}$ and $^{14}$C dates (2) derived from core subsamples. $^{210}\text{Pb}$ and $^{14}$C dates were obtained from the Australian Nuclear Science and Technology Organisation (ANSTO), Sydney, and DirectAMS, Washington, and resulting dates were used to build a Plum age-depth model using the ‘plum’ package in R (Blauw et al. 2021; R Core Team 2020), with $^{14}$C dates calibrated using the SHCal20 dataset (Hogg et al. 2020). Plum is an age-depth modelling method that employs Bayesian statistics to build accumulation histories for $^{210}\text{Pb}$-dated deposits using prior information and can combine $^{210}\text{Pb}$ and radiocarbon dates in the chronologies (Aquino-López et al. 2018; Blauw et al. 2021). Sample depths with exotic Pinus pollen in other shorter records are used as a marker for post-European settlement period.

For fire history reconstruction, contiguous subsamples were taken in sediment cores for macroscopic charcoal (> 125 µm) analysis following the method of Whitlock and Larsen (2001), which involves bleaching and sieving. Macroscopic charcoal particles were expressed as charcoal accumulation rates (CHAR; particles/cm²/year) for CS records and as concentrations for other shorter records (particles/cm³) without chronologies. Microscopic charcoal particles (< 125 µm) were also recorded for CS in pollen slides (transect method, about half of each slide) and expressed as accumulation rates using Lycopodium spike-based concentration estimate.

Sediment cores were subsampled at 2-cm interval and analysed for pollen following standard pollen preparation approach, including HCl, KOH and acetolysis (Faegri and Iversen 1975), to reconstruct vegetation history. At least 300–400 terrestrial pollens were identified in most samples (especially in Copping’s Swamp), whilst about 20–100 terrestrial pollens were identified in the basal part (> 10 cm) of other cores due to extremely low pollen concentrations. The main pollen sum was formed by the sum of terrestrial trees, shrubs and herbs, whilst aquatic and spore sums were calculated relative to the main pollen sum. Non-pollen palynomorphs (NPPs) were also counted in pollen slides and percentages were calculated relative to the main pollen sum. Lycopodium spike (Batch no. 3862, 9666 spores) was added to estimate pollen concentrations, which is then used to calculated pollen accumulation rates (PAR; pollen grains/cm²/year) for CS record. Pollen diagrams were generated using Tilia 3.0.1 (https://www.tiliait.com). Granger causality tests were performed on the record to test lagged relationships between vegetation groups (heathland and scrub/forest) and fire activity (CHAR), and tests were conducted for up to a total of 4 lag steps. Granger causality tests were performed in R (R Core Team 2020) using the `lmtest` package (Zeileis and Hothorn 2021).

**Historical aerial photography analysis**

To map historical vegetation changes, aerial photographs covering Cape Pillar were acquired from Land Tasmania (https://nre.tas.gov.au/land-tasmania), for the years 1946, 1980 and 2010, orthorectified with ± 5-m accuracy. To maximise comparability between photos, we resampled each
image to a resolution of 1 m and, where colour imagery was available, we converted them to greyscale.

Image classification was performed for the area within 500-m distance from any core site, excluding the cliffs due to high image distortion and shading (Fig. 6a), combining spectral and textural information. Textural measures of smoothness, coarseness and regularity were obtained using Grey-Level Co-Occurrence Matrix (GLCM; Haralick et al. 1973) using the package ‘gclm’ (Zvoleff 2020) in R (R Core Team 2020). GLCM evaluates the distribution of co-occurring pixel values by moving a window of pixels across the image; as the chosen window size influences classification accuracy, we calculated, for a sample image (i.e. imagery for the year of 1946), texture parameters for four different sliding windows that have been used in similar studies (e.g. Chen et al. 2020; Kupidura et al. 2019; Murray et al. 2010): 9×9, 15×15 and 21×21.

We classified the aerial photographs using the ‘RStoolbox’ R package (Leutner et al. 2019) and Random Forest algorithm, which have been shown to provide accurate vegetation classification results (e.g. Chen et al. 2020; Kupidura et al. 2019). For each photograph, we generated a training dataset which included the following vegetation classes: burnt, heathland, scrub and forest. The training dataset was split 70/30, meaning that 70% of data points were used to train the algorithm and 30% to evaluate classification accuracy using overall accuracy and Kappa coefficients. The window of size 21×21 was associated with the highest overall accuracy and Kappa values in the sample image and as such it was used to classify all remaining images (Table S1 in Appendix S3). Post-classification processing was then conducted in ArcMap™ 10.8 (ESRI) to remove isolated pixels.

Results

Lithology and chronology

Copping’s Swamp (CS) is characterised by red-brown sandy peat from 60 to 50 cm, silty peat from 50 to 10 cm and black coarse peat in the top 10 cm (Fig. 3). Teddy’s Pond (TP) is composed of sandy sediment with low organics from 16.5 to 9.5 cm and black silty peat in the top 9.5 cm (Fig. 4). Perdition Pond (PP) is composed of sand from 38 to 14 cm, sand with low organics from 14 to 10.5 and dark grey silty clay in the top 10.5 cm (Fig. 4). Snake Head Pond (SHP) is composed of sandy organic sediment from 17 to 8 cm and black silty peat in the top 8 cm (Fig. 4).

Plum age-depth model suggests a basal (60 cm) age of ~2523 calendar years before present (cal yr BP) for CS, with the timing of European arrival sitting at 16 cm (143 cal yr BP or 1807 AD) and highest sedimentation rates after 1807 AD (Fig. 2; Tables 1 and 2). Exotic Pinus pollen, which is indicative of post European arrival (post-1803 AD), is present in the top samples of PP. Minor occurrence of Pinus in TP and SHP is likely due to the records’ extremely low pollen concentration (Fig. 2).

Terrestrial vegetation, fire-regime and wetland reconstruction

In CS, Ericaceae taxa, Restionaceae and Casuarinaceae were generally well-represented throughout the record at ~20% each, respectively. However, Selaginella was abundant (20%) at the base of CS between 60 and 40 cm (<1400 cal yr BP) and Ericaceae and Restionaceae gradually declined from 16 cm (~143 cal yr BP; 1807 AD), dropping further after 10 cm (~13 cal yr BP; 1958 AD) to ~5–10% in favour of Banksia, Melaleuca, Leptospermum and Kunzea ambigua. CS macro and micro charcoal accumulation rates (CHAR) follow similar trends and only the former is presented here (see Fig. S1 in Appendix S4 for micro CHAR result). Macro CHAR and PAR were low (<10 particles/cm²/yr and <50 grains/cm²/yr, respectively) before 1807 AD in CS and increased after this time to >20 particles/cm²/yr and >100 grains/cm²/yr, respectively. Freshwater algae were well-represented before 1807 AD and were replaced by fungal spores and testate amoebae after this time (Fig. 3).

Casuarinaceae (40–80%) dominates TP, with Eucalyptus abundance between 10 and 4 cm, reaching ~80%. Charcoal concentrations gradually increased from 8 cm (<20 particles/cm³) and peaked in the top 2 cm (>20 particles/cm³). Aquatic macrophytes and freshwater algae were abundant in the record; however, the latter declined after 8 cm (Fig. 4).

Casuarinaceae and Banksia dominate the top 14 cm of PP record, accounting for ~80% of total pollen abundance, whilst the sandy basal part (>14 cm) of the core is devoid of pollen. Charcoal concentrations were highest in the top 14 cm at >100 particles/cm³, and freshwater algae, including Chara macrofossil, are also present in this interval (Fig. 4). SHP record is also dominated by Casuarinaceae (~80%) and Banksia (~10%), but with Selaginella and Kunzea ambigua abundance between 8 and 4 cm at ~20 and 40%, respectively. The sandy basal part (>8 cm) of the core also lacks pollen and charcoal concentrations were high in the top 8 cm of the record (mostly >10 particles/cm³). Freshwater algae were abundant through the top 8 cm of the record (Fig. 4).

Terrestrial vegetation–fire relationship

Considering the length and quality of the sedimentary records, Granger causality tests were only conducted on CS sequence, which is the longest and the most robust in term of pollen count. Before 1807 AD, derived p-values from Granger causality tests show insignificant (p > 0.05) relationships between vegetation (heathland, scrub) and fire.
Conversely, significant relationship occurred between vegetation and fire when both vegetation groups and fire were used as lead predictors; the relationship occurred at least every 30 years (Fig. 5).

This is consistent with the results of the historical aerial photograph analysis, which showed that at least two large fires occurred in the area during the investigated 64 years (Fig. 6b), one in 1980 and one in the early 1940s. The area affected by the 1980 fire, as estimated by our vegetation analysis, matched the extent recorded in the ‘fire history’ dataset available from theLIST© State of Tasmania. As the Tasmanian fire history data do not report fires occurred during the first half of the twentieth century, we could not compare the estimated extent nor provide an exact year for the earlier fire. However, our vegetation analysis suggested that the fire likely occurred shortly before 1946, when the image was taken. Vegetation recovery, with transition from burnt to heathland to scrub, was observed for the burnt areas, whilst unburnt areas were characterised by scrub and forest expansion (Fig. 6b).
Fig. 4 Pollen and non-palynomorph records of major taxa/groups (> 5%) and lithology records for other shorter records from Cape Pillar, which include Perdition Pond, Snake Head Pond and Teddy’s Pond. Freshwater algae include Zygnemataceae species (Zygnema, Debarya) and pennate diatoms. Also shown is charcoal concentration record for each site. See supplementary info for full pollen and NPP records.

Table 1 $^{210}$Pb activity report for Copping’s Swamp, Cape Pillar, measured at the Australian Nuclear Science and Technology Organisation, Sydney.

| Depth (cm) | Lab ID | Density (g/cm$^3$) | Total $^{210}$Pb (Bq/kg) | Supported $^{210}$Pb (Bq/kg) | Unsupported $^{210}$Pb decay corrected (Bq/kg) |
|------------|--------|--------------------|---------------------------|-------------------------------|-----------------------------------------------|
| 0–2        | X528   | 0.32               | 160 ± 8                   | 2 ± 0                         | 160 ± 9                                       |
| 5–7        | X529   | 0.2                | 133 ± 6                   | 4 ± 1                         | 130 ± 6                                       |
| 6–10       | X530   | 0.256              | 114 ± 6                   | 6 ± 1                         | 109 ± 6                                       |
| 11–12      | X531   | 0.48               | 67 ± 3                    | 5 ± 0                         | 63 ± 3                                        |
| 12–14      | X532   | 0.613              | 45 ± 2                    | 4 ± 0                         | 41 ± 2                                        |
| 19–20      | X533   | 0.96               | 19 ± 1                    | 2 ± 0                         | 18 ± 1                                        |
Discussion

The historical records (Christie 1970; Calder 1985; Appendix 1 and 2, and Fig. 6) and palaeoecological data (Fig. 4) derived from Cape Pillar reveal substantial recent changes in vegetation, wetland and fire regimes in the Tasman Peninsula. These changes are most apparent in the Copping’s Swamp (CS) sequence that spans the late Holocene, whereas the other records only capture post-European environmental changes. Accordingly, this discussion focuses on the CS record (Fig. 7).

Pre-colonial environment in Cape Pillar

Prior to European settlement in the Tasman Peninsula in the early 1800s, Cape Pillar was likely dominated by a wet ericaceous open health (shrubby vegetation < 2 m tall), dominated by Sprengelia, with codominant rushes (Restionaceae) and moss-like ground cover (Selaginella) (Howells 2012). Considering the high pollen productivity of Casuarinaceae that is extremely common in Australian fossil pollen records, the percentage abundance at <20% suggests a very localised occurrence or long-distance dispersal signal in CS (Dodson 1983). Conversely, Poaceae (grass) has a low pollen productivity and underrepresentation in fossil pollen records, especially in Tasmania (Mariani et al. 2016, 2022); hence, the percentage at 5% may indicate a major presence around

| Depth (cm) | Lab ID     | 14C yr BP | Error (1σ) | Calendar age range |
|-----------|------------|-----------|------------|--------------------|
| 20        | D-AMS 045,057 | 165       | 24         | 217–289            |
| 35        | D-AMS 045,058 | 1462      | 18         | 1193–1362          |

Fig. 5 Granger causality test results for Copping’s Swamp, showing the significance levels of lagged relationships between changes in vegetation (pollen) and fire (CHAR) in 2 lag steps each in pre- and post-colonial periods. Heathland and scrub are the sum of respective pollen taxa shown in Fig. 3a

Table 2 AMS 14C date report for Copping’s Swamp, Cape Pillar, measured from DirectAMS, Washington
Cape Pillar before the nineteenth century. It is possible that patches of open grassland or grassy Casuarinaceae scrub/woodland were also present in the area prior to European colonialism in the early nineteenth century (Fig. 7).

Tasmanian heathland species are fire-adapted (frequent, low-moderate severity fires) and capable of resprouting after fires (Nicholson et al. 2017; Kirkpatrick and Harris 1999). Component heath species are also tolerant of impoverished substrates/sites, including waterlogged soils, which are unsuitable for trees (Lambers et al. 2010; Lamont and Keith 2017; Kirkpatrick and Harris 1999; Adeleye et al. 2021c). Although our Granger causality tests show insignificant relationships between vegetation and fire before European arrival, indigenous frequent low-intensity burning probably

Fig. 6  a Extent of the historical aerial photograph analysis, conducted within 500 m of the core sites (excluding the cliffs). The full area of the fire occurred in 1980 is shown. Basemap from Esri, DigitalGlobe, GeoEye, i-cubed, USDA FSA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo and the GIS User Community. b Historical vegetation changes occurred within the study area, showing the two detected large fires and the overall vegetation thickening.
contributed to the persistence of low-moderate fire-adapted heathland species, which over the longer term may have reduced soil nutrient accumulation, reinforcing long-term persistence of heathland in Cape Pillar (Bowman and Jackson 1981). This maintenance of open heathy vegetation by indigenous people may have in turn reduced the likelihood of large fire events in the area (low CHAR), due to low biomass fuel accumulation (low PAR) (Mariani et al. 2022).

Indigenous-maintained open heathland around Cape Pillar may have not only promoted a stable wetland and soil hydrology in the area but also increased freshwater resources for use (Adeleye et al. 2021d; McWethy et al. 2017). For instance, the presence of freshwater algae in CS, which is presently dominated by terrestrial vegetation, suggests this perched swamp, at least occasionally, supported water before the 1800s (Fig. 2). The abundance of sand (which is unfavourable for pollen preservation) in the basal portions of Snake Head Pond (SHP) and Perdition Pond (PP) prior to European colonisation may also indicate the presence of fast-flowing water in the ponds (most likely that the ponds are linked by a stream system) due to the prevailing open and frequently burned vegetation (Diaz et al. 2007; McGlone 2009; Woodward et al. 2014; Adeleye et al. 2021d).

Post-colonial environment in Cape Pillar

Cape Pillar treeless vegetation is currently dominated by scrub and tall heath defined as woody vegetation > 2 m tall (Kirkpatrick and Harris 1999). Major expansion of scrub species (Melaleuca, Leptospermum, Banksia, Casuarinaceae) occurred in CS from the beginning of the nineteenth century replacing heathland (Fig. 7). The increased abundance of Casuarinaceae and reduced grass pollen in other shorter records also likely reflect the expansion of Allocasuarina scrub/forest after European arrival. Additionally, Eucalyptus forest may have also expanded at Teddy’s Pond (TP) at some point during this period (Fig. 4). Granger causality tests show significant two-way (coupled) relationships between vegetation and fire after European arrival. However, the most statistically significant relationships were recorded when heathland was used as the leading predictor of fire, with decline in heathland vegetation resulting in major fires at least around every 30–45 years (Fig. 5).

European invasion of Tasmania was historically rapid given the British programme of transporting thousands of convicts to several localised, albeit geographically dispersed, penal settlements: overall European population in Tasmania
rose to > 20,000 by 1830 AD (Jones 1971). Frontier war, disease and a systematic government programme of removal led to a rapid depopulation of Aboriginal people from their ancestral homelands (Jones 1971). The accessible vegetation described by Europeans (James Calder) who visited Cape Pillar in the mid-nineteenth century was likely referring to the early phase of scrub expansion into the Cape’s heathland (Calder 1985), with dense scrub fully dominating by the 1960s, limiting access (Christie 1970). The cessation of traditional fire management due to the removal of indigenous people by the mid-nineteenth century likely drove the transition of heathland to taller and denser scrub in Cape Pillar. Increased soil nutrient availability associated with infrequent fires (Bowman and Jackson 1981) may have also contributed to the expansion of taller trees and shrubs that overtopped and suppressed shade-intolerant heathland communities (der Moral et al. 1978). Bargmann and Kirkpatrick (2015) in their multi-decadal study of heathlands in the Tasman Peninsula documented the transition of heathland to scrub between 1976 and 2013 due to the absence of fire. Our results suggest that this transition had likely started at least since the late 1940s and is strongly influenced by infrequent fire activity (Fig. 6b), likely caused by lightning. Increased biomass accumulation in scrub in CS, as reflected by high PAR, would have led to major fires events/episodes (high CHAR) every 3–4 decades, a pattern that is consistent with post-colonial fire regimes on the southeast Australian mainland (Mariani et al. 2022; Adeleye et al. 2021b) and fire occurrence in Tasmania today (Marsden-Smedley 2009; Ndalila et al. 2018; French et al. 2016; Nicholson et al. 2017).

The proliferation of peatland testate amoebae and fungal spores and a decline in freshwater algae at CS likely reflect increased vegetation density, wetland terrestrialization and reductions in wetland water supply and water levels. This shift in hydrological regimes may have been caused by reduced runoff associated with more closed canopy vegetation and increased transpiration load of shrub species.

### The potential role of climate in past environmental changes in Cape Pillar

Shifts in regional climate may have also influenced the environmental alterations at Cape Pillar, perhaps in combination with the cessation of indigenous fire management. Palaeoclimatic studies indicate drier conditions have prevailed across southeast Australia, including Tasmania, over the last two centuries as a result of increased precipitation variability (Gergis and Ashcroft 2013; Ashcroft et al. 2014). This drier climate is thought to have commenced from around the 1600s across eastern Australia due to Inter-decadal Pacific Oscillation (Palmer et al. 2015). Local palaeoclimate records, especially precipitation reconstructions, are currently scarce for the Tasmanian region. However, instrumental records show warming and decreasing precipitation over Tasmania since the 1900s (Climate Futures 2022). The replacement of freshwater algae assemblage by peatland testate amoebae and fungal spores in CS from the 1800s may potentially reflect this gradual onset of a drier climate, which then intensified after the 1900s (~1950 AD; 0 cal yr BP). Drier conditions at this time may have also led to a reduced fluvial energy in PP and SHP, with the prevalence of lentic waters and increased organic deposition in the catchments. Reduced waterlogged soil conditions as a result of the regional drier conditions may have contributed to the encroachment of scrub and woodland elements in areas that previously supported wet heathland communities (Adeleye et al. 2021c), with a major expansion of the former since the ~1950s.

### Management implications

Pollen records from Cape Pillar suggest that the current vegetation distribution and fire regime, at least in the southern edge of the Tasman Peninsula, are partly a product of skilful Aboriginal management that maintained open heath via a regime of low severity fires. Following European colonisation, fire became less frequent with corresponding increase in woody vegetation. Warmer and drier climates over the last century may have also contributed to this ecological shift. Accordingly, this study provides managers with an evidentiary basis to use frequent fires to maintain more open vegetation that is likely to burn less intensely and is more species rich (Bargmann and Kirkpatrick 2015). This is important because fire risk is increasing in Tasmania, evidenced by a recent spate of ecologically and economically destructive bushfires (Nicholson et al. 2017; Bowman et al. 2021; Ndalila et al. 2018; French et al. 2016), and the projections of worsening fire weather across the island due to climate change (Fox-Hughes et al. 2014). Fire management on Cape Pillar is increasingly important imperative because of substantial public and private tourism infrastructure investment and the risk of injury and death to tourists experiencing the Three Capes Track (Ellice-Flint 2017). Restoring the dense vegetation to open condition will be challenging given the risk of intense uncontrollable fires; hence, we recommend a programme of burning based on numerous small fires (<ha scale) on the edge of the track lit under low fire danger conditions.

### Conclusion

This study presents the first long-term detailed record of ecosystem change in the Tasman Peninsula, southeast Tasmania. We set out to understand pre- and post-colonial
changes in ecosystems and fire regimes in the area in order to gain insights into potential future changes and to inform management strategies in the area. Our results show the persistence of open heathland vegetation, hydrated wetlands and less wildfires prevailed at least in the southern Tasman Peninsula before European colonisation. Scrub largely replaced heathland after this time, with drained wetlands and increased wildfires after colonisation. Regional climate dynamics may have also contributed to this ecological shift. The analysis of additional sediment sequence from other parts of the Tasman Peninsula is recommended to fully understand spatio-temporal changes in vegetation and land use in region. Nonetheless, the results from this study provide a basis for ecosystem management of Cape Pillar. Continuous carefully managed burning aimed at restoring pre-colonial extensive open heathland-dominated landscape is recommended to help restore Aboriginal cultural landscapes and reduce the increasing risk of large fires driven by anthropogenic climate change. Our results are consistent with the idea that open landscapes maintained by indigenous people exist in many parts of Tasmania and southeast Australia in general before European colonisation and that the cessation of indigenous cultural land management after colonisation resulted in thickened/denser vegetation.

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References

Adelleye MA, Haberle SG, Connor SE, Stevenson J, Bowman DMJS (2021) Indigenous fire-managed landscapes in southeast Australia during the Holocene—new insights from the Furneaux Group Islands, Bass Strait Fire 4:17. https://doi.org/10.3390/fire4020017

Adelleye MA, Connor SE, Haberle SG, Herbert A, Brown J (2021) European colonization and the emergence of novel fire regimes in southeast Australia. Anthr. https://doi.org/10.1177/20530196211044630

Adelleye MA, Haberle SG, Harris S, Hopf FV-L, Connor S et al (2021) Holocene heathland development in temperate oceanic Southern Hemisphere: key drivers in a global context. J Biogeogr 48:1048–1062. https://doi.org/10.1111/jbi.14057

Adelleye MA, Haberle SG, Harris S, Connor SE, Stevenson J (2021) Assessing long-term ecological changes in wetlands of the Bass Strait Islands, southeast Australia: palaeoecological insights and management implications. Wetlands 41:88. https://doi.org/10.1007/s13157-021-01480-z

Aquino-López MA, Blaauw M, Christen JA, Sanderson NK (2018) Bayesian analysis of 210Pb dating. JABES 23:317–333. https://doi.org/10.1080/13250180.2014.991097

Aschcroft L, Karoly DJ, Gergis J (2014) Southeastern Australian climate variability 1860–2009: a multivariate analysis. Int J Climatol 34:1928–1944. https://doi.org/10.1002/joc.3812

Australian Bureau of Meteorology (2013) Tasmania in January 2013: record heat, little rain. http://www.bom.gov.au/climate/current/month/tas/archive/201301.summary.shtml. Accessed August 2021

Banks MR, Colhoun EA, Ford RJ, Williams E (1989) A reconnais-sance geology and geomorphology of Tasman Peninsula. In: Smith SJ (ed) Is history enough? Past, present and future use of the resources of Tasman Peninsula. Royal Society of Tasmania, Hobart, pp 7–23

Bargmann T, Kirkpatrick JB (2015) Transition from heathland to scrub in south-eastern Tasmania: extent of change since the 1970s, flori- stic depletion and management implications. Biodivers Conserv 24:213–228. https://doi.org/10.1007/s10531-014-0803-6

Blaauw M, Christen A, Aquino-Lopez M (2021) rplum: Bayesian age-depth modelling of cores dated by Pb-210. CRAN. https://cran.r-project.org/web/packages/rplum/rplum.pdf. Accessed August 2021

Bowman DMJS (1998) The impact of Aboriginal landscape burning on the Australian biota. New Phytol 140:385–410. https://doi.org/10.1111/j.1469-8137.1998.00289.x

Bowman DMJS, Jackson W (1981) Vegetation succession in southwest Tasmania. Hobart, pp 33–50

Bowman DMJS, Wood SW, Neyland D, Sanders GJ, Prior LD (2013) Contracting Tasmanian montane grasslands within a forest matrix is consistent with cessation of Aboriginal fire management. Austral Ecol 38:627–638. https://doi.org/10.1111/aece.12008

Bowman DM, Rodriguez-Cubillo D, Prior LD (2021) The 2016 Tasmanian wilderness fires: fire regime shifts and climate change in a Gondwanan biogeographic refugium. In: Canadell JG, Jackson RB (ed) Ecosystem collapse and climate change, vol 241. Ecological Studies, Springer, Cham. https://doi.org/10.1007/978-3-030-71330-0_6

Brown MJ, Duncan F (1989) The vegetation of Tasman Peninsula. In: Smith SJ (ed) Is history enough? Past, present and future use of the resources of Tasman Peninsula. Royal Society of Tasmania, Hobart, pp 33–50

Bui E, Hancock G, Chappell A, Gregory L (2010) Evaluation of tolerable erosion rates and time to critical topsoil loss in Australia. CSIRO Publishing. https://doi.org/10.25919/Sc5c.72283f34

Calder J (1985) Rambles on Betsey’s Island, Tasman’s Peninsula, and Forestier’s Peninsula in February 1848. Sullivan’s Cove, Adelaide
Chen Z, Fei X, Gao X, Wang X, Zhao H et al (2020) The influence of CLBP window size on urban vegetation type classification using high spatial resolution satellite images. Remote Sens 12:3393. https://doi.org/10.3390/rs1203393

Christie T (1970) Cape Pillar. Tasmanian Tramp J Hobart Walk Club 19

Climate Future (2022) Climate futures for Tasmania. Technical report. https://climatefutures.org.au/projects/climate-futures-tasmania/ Accessed August 2021

Cullen P, Dell M (2011) Geomorphology and geoheritage values along the route of the proposed Three Capes Walking Track, Tasman Peninsula, Tasmania. A Report for the Parks and Wildlife Service, Tasmania

Department of Primary Industries, Water and Environment (2012) Development application to Tasman council for the Three Capes Track. Parks and Wildlife Service, Department of Primary Industries, Parks, Water and Environment, Hobart

der Moral R, Willis RJ, Aston DH (1978) Suppression of coastal heath vegetation by Eucalyptus baxteri. Aust J Bot 26:203–219. https://doi.org/10.1071/ BT9780203

Diaz MF, Bigelow S, Armesto JJ (2007) Alteration of the hydrologic cycle due to forest clearing and its consequences for rainforest succession. For Ecol Manag 244:32–40. https://doi.org/10.1016/j.foreco.2007.03.030

Dodson JR (1983) Modern pollen rain in southeastern New South Wales, Australia. Rev Palaeobot Palynol 38:249–268. https://doi.org/10.1016/0034-667X(83)90025-8

Elliffe-Flint J (2017) Three Capes Track. Landscape. Archit Aust 156:73–81

Ens E, Clarke P, Walsh F (2017) Aboriginal people and Australia’s vegetation: past and current interactions. In: Keith D (ed) Australian vegetation, 3rd edn. Cambridge University Press, pp 89–112

Faegri K, Iversen J (1975) Textbook of pollen analysis. Hafner Press, New York

Fletcher MS, Hall T, Alexandra AN (2021) The loss of an indigenous constructed landscape following British invasion of Australia: an insight into the deep human imprint on the Australian landscape. Ambio 50:138–149. https://doi.org/10.1007/s13280-020-01339-3

Fournes JA, Prior LD, Leonard SW, Bowman DM (2021) Demographic effects of severe fire in montane shrubland on Tasmania’s central plateau. Fire 4:32. https://doi.org/10.3390/fire4030032

Fox-Hughes P, Harris R, Lee G, Grose M, Bindoff N (2014) Future fire danger climateology for Tasmania, Australia, using a dynamically downscaled regional climate model. Int J Wildland Fire 23:309–321. https://doi.org/10.1071/WF13126

French B, Prior L, Williamson G, Bowman D (2016) Cause and effects of a megafire in sedge-heathland in the Tasmanian temperate wilderness. Aust J Bot 64. https://doi.org/10.1071/ BT16087

Gammage B (2008) Plain facts: Tasmania under Aboriginal management. Landsc Res 33:241–254. https://doi.org/10.1080/0142390701767278

Gammage B (2011) The biggest estate on earth. Allen and Unwin, Melbourne

Gergis J, Ashcroft L (2013) Rainfall variations in south-eastern Australia part 2: a comparison of documentary, early instrumental and palaeoclimate records, 1788–2008. Int J Climatol 33:2973–2987. https://doi.org/10.1002/joc.3639

Hallam SJ (2014) Fire and hearth: a study of Aboriginal usage and European usurpation in south-western Australia. Revised edition by Mulvaney J. Apollo Books

Haralick RM, Shanmugam K, Dinstein HI (1973) Textural features for image classification. IEEE Trans Syst Man Cybern Syst 6:610–621. https://doi.org/10.1109/TSMC.1973.4309314

Harle KJ, Britton K, Heijnis H, Zawadzki A, Jenkinson AV (2002) Mud, mines and rainforest: a short history of human impact in western Tasmania, using pollen, trace metals and lead-210. Aust J Bot 50:481–497. https://doi.org/10.1071/ BT01028

Hogg A, Heaton T, Hua Q, Palmer J, Turney C et al (2020) SHCal20 southern hemisphere calibration, 0–55,000 years cal BP. Radiocarbon 62:759–778. https://doi.org/10.1017/RDC.2020.59

Howells C (2012) Tasmania’s natural flora. Australian Plant Society Tasmania Incorporated, Hobart Group

Jackson WD (1968) Fire, air, water and earth—an elementary ecology of Tasmania. Proc Ecol Soc Aust 3:9–16

Jackson WD (1968) Fire and the Tasmanian flora. In: Tasmanian yearbook 1968. Department of Science, Melbourne 50–55

Jones R (1971) The demography of hunters and farmers in Tasmania. In: Molvaney DJ, Golson J (eds) Aboriginal man and environment in Australia. Australian National University Press, pp 271–287

Jones PJ, Williamson GI, Bowman D, Lefroy EC (2019) Mapping Tasmania’s cultural landscapes: using habitat suitability modeling of archaeological sites as a landscape history tool. J Biogeogr 1–13. https://doi.org/10.1111/jbi.13684

Kirkpatrick J (1994) A continent transformed: human impact on the natural vegetation of Australia. Oxford University Press

Kirkpatrick JB, Harris S (1999) The disappearing heath revisited. Tasmanian Environment Centre Hobart

Kupidura P, Osinska-Skotak K, Lesisz K, Podkowa A (2019) The efficacy analysis of determining the wooded and shrubbed area based on archival aerial imagery using texture analysis. ISPRS Int J Geo-Inf 8:450. https://doi.org/10.3390/ijgi8100450

Lambers H, Brundrett MC, Raven JA, Hopper SD (2010) Plant mineral nutrition in ancient landscapes: high plant species diversity on fertile soils is linked to functional diversity for nutritional strategies. Plant Soil 334:11–31. https://doi.org/10.1007/s11104-010-0444-9

Lamont BB, Keith DA (2017) Heathland and associated shrublands. In: Keith DA (ed) Australian vegetation. Cambridge University Press, Cambridge, pp 340–367

Land Tasmania (2017). Land information system Tasmania. Department of Natural Resources and Environment Tasmania. https://www.thelist.tas.gov.au/app/content/home Accessed August 2021

Leaman D (1999) Walk into history in southern Tasmania. Leaman Geophysics, Hobart, Tasmania

Leutner B, Horning N, Schwalb-Willmann J (2019) RStoolbox: tools for remote sensing data analysis. R package version 0.2.6. https://cran.r-project.org/web/packages/RStoolbox/RStoolbox.pdf. Accessed Aug 2021

Mariani M, Connor SE, Theuerkauf M, Kuneš P, Fletcher MS (2016) Testing quantitative pollen dispersal models in animal-pollinated vegetation mosaics: an example from temperate Tasmania, Australia. Quat Sci Rev 154:214–225. https://doi.org/10.1016/j.quascirev.2016.10.020

Mariani M, Connor S, Theuerkauf M, Herbert A, Kuneš P et al (2022) Disruption of cultural burning promotes unprecedented wildfires. Front Ecol Environ 20:292–300. https://doi.org/10.1002/fee.2395

Marsden-Smedley J (2009) Planned burning in Tasmania: operational guidelines and review of current knowledge. Department of Primary Industries, Parks, Water and Environment. http://www.fire.tas.gov.au/userfiles/stuart/file/Publications/PlannedBurningInTasmania.pdf. Accessed Aug 2021

McGlone MS (2009) Postglacial history of New Zealand wetlands and implications for their conservation. N Z J Ecol 33:89–112

McWethy DB, Haberle SG, Hopf F, Bowman DMJS (2017) Aboriginal impacts on fire and vegetation on a Tasmanian island. J Biogeogr 44:1319–1330. https://doi.org/10.1111/jbi.12935

Moss PT, Gehrels WR, Callard SL (2016) European impacts on coastal eastern Tasmania: insight from a high-resolution palynological analysis of a salt-marsh core. Front Ecol Evol 4. https://doi.org/10.3389/fevo.2016.00105
Murray H, Lucieer A, Williams R (2010) Texture-based classification of sub-Antarctic vegetation communities on Heard Island. Int J Appl Earth Obs Geoinf 12:138–149. https://doi.org/10.1016/j.jag.2010.01.006

Ndalila MN, Williamson GJ, Bowman DMJS (2018) Geographic patterns of fire severity following an extreme Eucalyptus forest fire in southern Australia: 2013 Forcett-Dunalley fire. Fire 1:40. https://doi.org/10.3390/fire1030040

Nicholson Á, Prior LD, Perry GL, Bowman DM (2017) High post-fire mortality of resprouting woody plants in Tasmanian Mediterranean-type vegetation. Int J Wildland Fire 26:532–537. https://doi.org/10.1071/WF16211

Palmer J, Cook ER, Turney CSM, Allen K, Fenwick P et al (2015) Drought variability in the eastern Australia and New Zealand summer drought atlas (ANZDA, CE 1500–2012) modulated by the Interdecadal Pacific Oscillation. Environ Res Lett 10:124002–124013. https://doi.org/10.1088/1748-9326/10/12/124002

R Core Team (2020) R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna (http://www.R-project.org/)

Romanin LM, Hopf F, Haberle SG, Bowman DM (2016) Fire regime and vegetation change in the transition from Aboriginal to European land management in a Tasmanian eucalypt savanna. Aust J Bot 64:427–440. https://doi.org/10.1071/BT16032

UNESCO World Heritage Convention (2007) Porth Arthur. Department of the Environment water Heritage and the Arts. https://whc.unesco.org/en/documents/114746. Accessed Aug 2021

Whitlock C, Larsen C (2001) Charcoal as fire proxy. In: Smol P, Birks HJB, Last WM (ed) Tracking environmental change using lake sediments: terrestrial, algal, and siliceous indicators. Kluwer Academic Publishers, Dordrecht, The Netherlands

Woinarski JC, Burbidge AA, Harrison PL (2015) Ongoing unravelling of a continental fauna: decline and extinction of Australian mammals since European settlement. PNAS 112:4531–4540. https://doi.org/10.1073/pnas.1417301112

Woodward C, Shulmeister J, Larsen J, Jacobsen GE, Zawadzki A (2014) The hydrological legacy of deforestation on global wetlands. Science 346:844–847. https://doi.org/10.1126/science.1260510

Zeileis A, Hothorn T (2021) Diagnostic checking in regression relationships. R News 2:7–10. https://CRAN.R-project.org/doc/Rnews/. Accessed Aug 2021

Zvoleff A (2020) glcm: calculate textures from grey-level co-occurrence matrices (GLCMs). R Package Version 1(6):5. https://doi.org/10.1109/TSMC.1973.4309314

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