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Fire activity and deforestation in Remote Oceanian islands caused by anthropogenic and climate interactions

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Remote islands in the Pacific Ocean (Oceania) experienced dramatic environmental transformations after initial human settlement in the past 3,000 yr. Here, human causality of this environmental degradation has been unquestioned and viewed as evidence of the inherent destructive tendencies of human societies in both archaeological and popular discourse. We use charcoal and stable carbon isotopes from deep soil cores to reconstruct the dynamics of fire activity and deforestation across the Sigatoka River valley on the leeward (dry) side of Viti Levu, Fiji. Fires and pyrogenic patches of grassland predated human settlement by millennia, but the magnitude of fire activity and landscape transformation accelerated with the establishment and expansion of swidden agriculture. Regional comparisons with previous studies in Fiji and elsewhere in Remote Oceania settled between 3,200 and 2,900 yr BP reveal a similar pattern of pre- and post-settlement fire activity and landscape change. Pre-settlement fires generally corresponded to droughts, probably driven by El Niño, often correlating with drought-driven wildfires elsewhere in the region. Post-settlement, charcoal and C_4 grasses increased dramatically, but nearly all major peaks in charcoal and grasses corresponded to increased El Niño activity. This indicates that fire activity and deforestation were a product of the interaction between swidden agriculture and climate rather than land use alone.

The degradation of remote Pacific islands after the first human settlement has become a modern environmental parable, illustrating the potentially irreversible consequences of deforestation and soil exhaustion on a limited Earth[1]. Regional archaeobiological syntheses have corroborated this interpretation, documenting accelerated vegetation turnover after settlement[2]. Other syntheses have identified the key geographic factors that made some islands more vulnerable to anthropogenic environmental change than others[3,4], but the anthropogenic origin of this deforestation has been largely unquestioned. This narrative has been used to argue that anthropogenic environmental degradation is an inherent part of any society, thus bolstering one feature of the 'wilderness myth' in which the only way to preserve the natural world is to exclude humanity[1,5]. This narrative that Oceanic fire activity was exclusively anthropogenic stands in contrast to regional-scale fire history analyses in Australasia that highlight the important role of climate in fire activity over the past 70,000 yr despite widespread human fire use[6] and recent observations of the interaction between human ignitions and climate on fire activity in tropical forests

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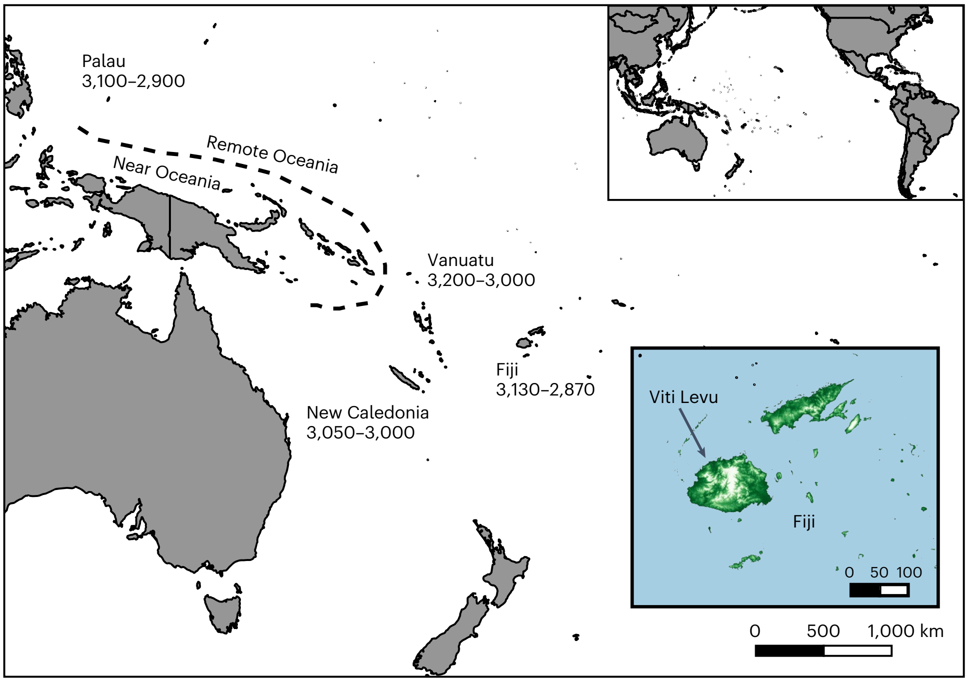

Fig. 1 | Map of Near and Remote Oceania settled at ca. 3,200–2,900 yr BP. The locations of Fiji and Viti Levu are indicated. Dates for the earliest settlement[9] of Palau, Vanuatu, New Caledonia and Fiji are indicated on the main map. Elevation data are from the Copernicus 90 m dataset. Map credits: C.I.R.

of the region[7]. The most dramatic example of this was the combined role of El Niño drought and anthropogenic ignitions on major regional fire events of recent decades[8].

People of the Lapita Culture began migrating beyond New Guinea, the Bismarck Archipelago and the Solomon Islands (Near Oceania) into the island chains to the north and southeast (Remote Oceania) after 3,500 yr BP, settling in parts of Micronesia to the north and Fiji, Vanuatu and New Caledonia to the southeast variously between ca. 3,200–2,900 yr BP (Fig. 1)[9]. Lapita voyagers brought 'transported landscapes' of plants and animals of horticultural and economic value, including staple crops of taro (*Colocasia esculenta*) and yam (*Dioscorea* spp.)[10]. Yam cultivation in particular would have required forest clearing as part of a shifting swidden (slash-and-burn) dryland cultivation strategy[11].

Modern El Niño Southern Oscillation (ENSO) patterns emerged in the past 6,000–5,000 yr, with greatest frequencies of El Niño (warm phase) events in the past 3,000 yr (refs. 12–15). Archaeologists have speculated that the increase in El Niño frequencies at ca. 3,000 yr BP may have facilitated the Lapita expansion by weakening trade winds[16]. El Niño events are associated with severe droughts in the western Pacific[17], particularly on the leeward side of larger islands[18], and have triggered changes in fire activity as far afield as Indonesia[8], southeast Australia[19] and Tasmania[20]. Other evidence for regional droughts in the Western Pacific Warm Pool (WPWP) are dynamic peatland wildfire records over the past 6,000 yr, much of which may relate to Pacific Ocean climate variability and ENSO[21]. Much of Remote Oceania in the western Pacific falls within the region impacted by drought during El Niño events[22], including increased forest fire activity during these events[23]. Pacific islands are also particularly vulnerable to the 'grass–fire cycle', wherein grasslands facilitate further expansion of grasses by enhancing flammability and fire spread[24]. We hypothesize that El Niño and other WPWP droughts impacted fire activity and deforestation both before and after first settlement of Remote Oceania ca. 3,200–2,900 yr BP. Fallowed agricultural fields with heavy grass cover could have been highly flammable pathways for further unintended deforestation from 'fire leakage' when droughts increased flammability[25]. If this hypothesis is valid, expanded fire activity and deforestation need not have been a direct consequence of slash-and-burn intensification[26] but could have been an emergent phenomenon associated with swidden cultivation and periods of enhanced climate vulnerability.

We evaluate this hypothesis with a multiscale analysis of fire and vegetation change in drought-prone contexts in Remote Oceania. Viti Levu is the largest island in Fiji (Fig. 1) and the fourth largest island in Remote Oceania. Before human settlement, the leeward (dry) side of Viti Levu was covered with tropical dry forest[27]. On the leeward side of Viti Levu today, the Sigatoka River winds through grassland and savannah (locally called 'talasiga'), and some remaining patches of dry forest in the central and southwestern part of the island (Fig. 2). Archaeology at the Sigatoka Dunes site at the mouth of the Sigatoka River suggests local Lapita occupation by 2,600 yr BP (ref. 28) and settlement of the interior of the Sigatoka valley had occurred by 2,000 yr BP (ref. 29). The oldest known Lapita site in Fiji is Bourewa, located just 25km to the west, which was established between 3,200 yr BP and 2,900 yr BP (ref. 30). Direct dating of charcoal from archaeological sites at Bourewa[30], Sigatoka Dunes[28,31] and across the Sigatoka River Valley[29] lays out the general chronology for minimum ages for first settlement, inland settlement, the establishment of hillforts and conflict, as well as subsequent waves of migration to the area[31], much of which is generally corroborated from archaeological sites across Viti Levu and other Fijian islands.

To assess the timing and spatial pattern of swidden farming and deforestation following colonization, we conducted a terrestrial soil coring programme focused on tributary drainages of the Sigatoka River extending inland from the coast to the oldest known interior site, Tatuba Cave[29]. We measured soil charcoal concentrations to reconstruct fire activity and stable carbon isotopes of soil organic matter to reconstruct the dynamics between C_3 woody vegetation and C_4 grasses. Here we compare these fire and vegetation histories from across the Sigatoka valley with fire records from elsewhere in Fiji, New Caledonia and Vanuatu, and from Palau in Micronesia—all areas in Remote Oceania influenced by El Niño droughts, with settlement histories beginning ca. 3,000 yr BP. We evaluate these trends in tandem with proxy records for El Niño frequencies[12,15] and wildfire proxies for drought elsewhere in the

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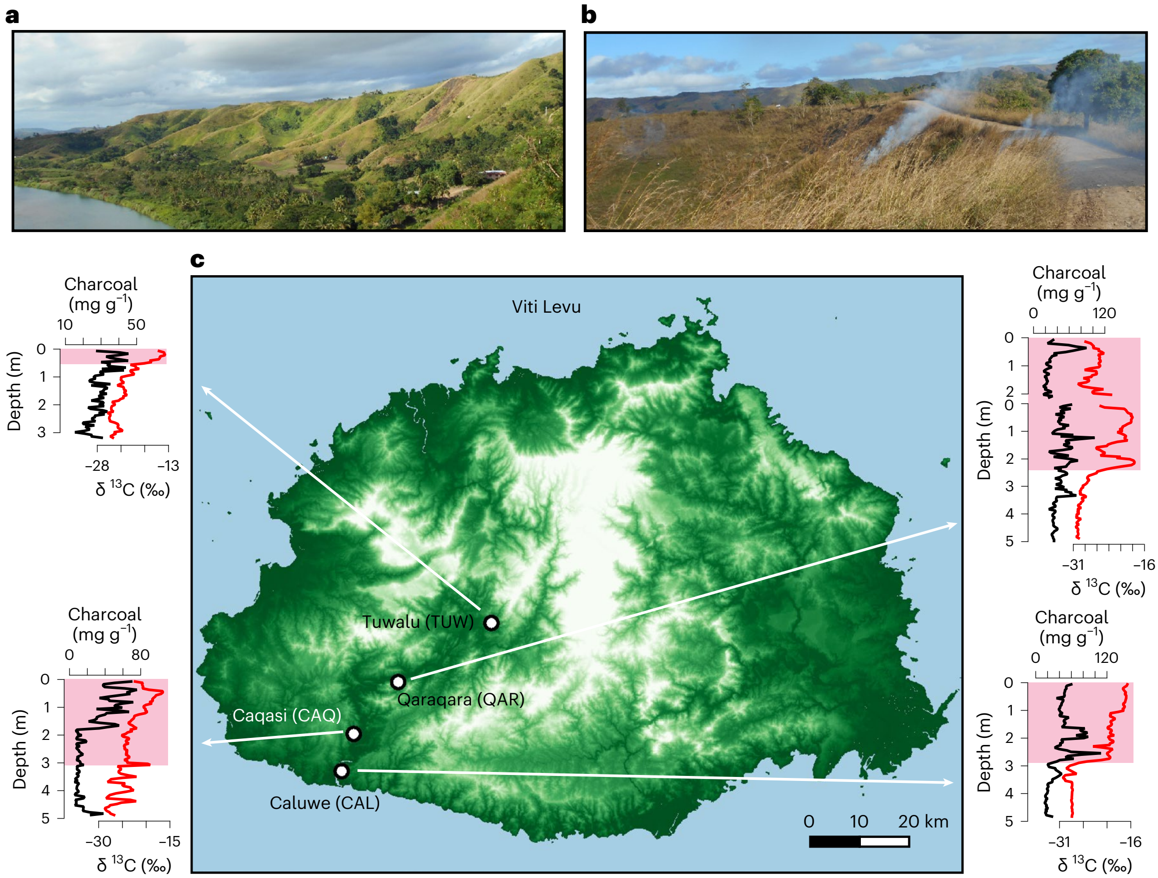

Fig. 2 | Stratigraphic records of charcoal and stable carbon isotopes from Viti Levu. a–**c**, Photos of grasslands (**a**) and grassland fires (**b**) in the Sigatoka River valley of Viti Levu (**c**). The leeward (dry) side of Viti Levu is largely 'talasiga' or grassland/savanna on the west/northwest side of the island. Stratigraphic charcoal concentrations (black lines) and $\delta^{13}C$ ratios (red lines) for each coring location are plotted by depth, with strata deposited during human occupation highlighted by the pink areas. Elevation data are from the Copernicus 90 m dataset. Photo and map credits: C.I.R.

WPWP[21] to assess the relative importance of land use and climate on fire activity and deforestation in Remote Oceania. While these ENSO and WPWP drought proxies are imperfect[32], they provide a useful heuristic for long-term variability in Pacific Ocean-driven climate against which to compare our records.

Results

The Caluwe Creek valley is the first valley encountered on the east side of the Sigatoka River upstream from the coast, less than 3 km from the mouth of the river and the Sigatoka Dunes Lapita site (Fig. 2c). The Caluwe core (CAL) exposed 4.8 m of sediments and soils with two different lithologic units and four soil stratigraphic units in fine-grained overbank flood deposits overlying wetland deposits (Extended Data Fig. 1). Radiocarbon dates indicate that these cores span the past 7,200 yr, with a hiatus in deposition between the two lithological strata between ca. 2,800 and 1,800 yr BP (ref. 11). Charcoal was at very low levels in pre-settlement wetland strata and increased dramatically in post-settlement overbank flooding sediments and two stratified weakly developed soils after the lithologic break. This pattern is replicated in the stable carbon isotope data where $\delta^{13}C$ values were substantially depleted in pre-settlement strata and substantially enriched after the hiatus.

The Caqasi Creek valley is ~14 km upriver from the mouth of the Sigatoka River on the north/west side (Fig. 2c). The Caqasi core (CAQ) exposed 4.8 m of sediments and soils from an alluvial terrace displaying alternating fine-grained overbank flood deposits and coarse-grained channel and bar deposits, with five soil stratigraphic units overprinted on these deposits (Extended Data Fig. 2). Charcoal was moderately high in fine-grained deposits at the base of the core (ca. 7,200 yr BP) but very low through most of the core when sediments were dominated by gravel and sand. Charcoal concentrations were high in fine-grained overbank deposits of the upper 1.7 m (past 800 yr). Low charcoal concentrations in channel and bar deposits below this cannot be interpreted as periods of low fire activity as these sedimentary environments are not conducive to charcoal deposition[33,34]. However, small amounts of organic matter were deposited throughout the core regardless of sediment lithologies, revealing an essentially continuous record of vegetation from stable carbon isotopes. $\delta^{13}C$ values were generally depleted in pre-settlement strata, with periodic peaks in enriched values. There was an acute peak in enriched $\delta^{13}C$ values at ~3 m (ca. 3,000 yr BP), followed by higher $\delta^{13}C$ values that increased further in the upper 1.7 m.

The Qaraqara Creek valley is located ~48 km upriver from the mouth of the Sigatoka River on the south/east side (Fig. 2c). There were two alluvial terraces in this valley and each was cored (QAR). Coring exposed 5 m of alluvium overprinted with five stratified soils from the older, upper terrace spanning ca. 5,000–600 yr BP (Extended Data Fig. 3). Coring exposed 2.1 m of alluvial sediments and two soil stratigraphic units within overbank alluvium from the younger inset terrace spanning the past 600 yr (Extended Data Fig. 4). Charcoal was generally lower in pre-settlement strata, apart from a prominent peak at ~3.2 m (ca. 3,500 yr BP). Charcoal concentrations were high and variable through most of the post-Lapita period until they declined in the younger terrace. Stable carbon isotope ratios were substantially depleted in pre-settlement strata but became very enriched

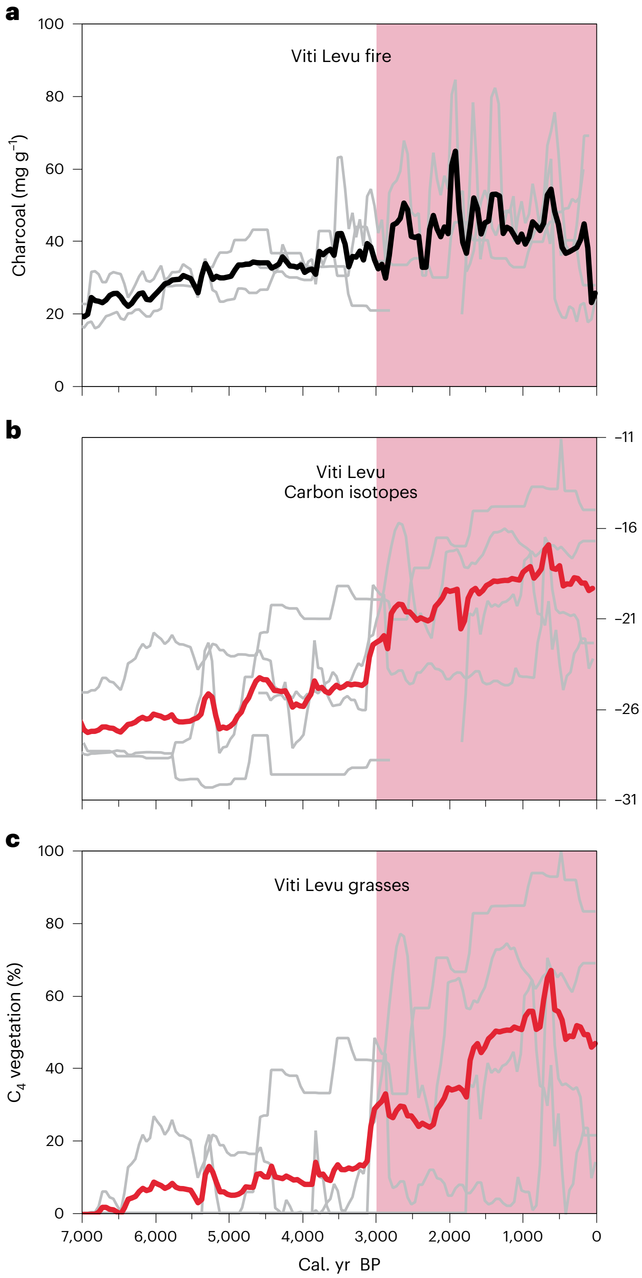

Fig. 3 | Fire and vegetation histories from the Sigatoka Valley. a–**c**, Synthesis of charcoal concentrations (black line) (**a**), $\delta^{13}C$ ratios (red line) (**b**) and percentage of C_4 vegetation (red line) (**c**) for the Sigatoka valley coring programme. Thin grey lines indicate individual coring localities. Thick lines indicate the average values for all localities. Samples with >3% gravel were excluded from consideration in the charcoal records.

above 2.4 m until a slight decline at the top 0.1 m of the old terrace and throughout the younger terrace.

The Tuwalu Creek valley is located ~73 km upriver from the mouth of the Sigatoka River on the north/west side (Fig. 2c) and less than 2 km from the Tutuba Cave archaeological site. Coring (TUW) exposed 3.1 m of alluvial and colluvial sediments spanning 12,600 yr BP, with two stratified soils (Extended Data Fig. 5). Charcoal concentrations were generally low before peaks at 0.7 and 0.6 m (ca. 3,700 and 3,100 yr BP), after which charcoal concentrations remained generally high. Stable carbon isotope ratios gradually became more enriched over the past 12,000 yr BP, with substantially enriched $\delta^{13}C$ values after 0.5 m (2,500 yr BP).

By synthesizing the records from all four watersheds in the Sigatoka valley over the past 7,000 yr, we see a general pattern emerging (Fig. 3). Before Lapita settlement at ca. 3,000 yr BP, charcoal concentrations gradually increased over time (mean concentration, 30.8 mg g^{-1}), with five pronounced peaks between 5,600 and 3,200 yr BP (1.8 peaks per 1,000 yr; maximum concentration, 42.3 mg g^{-1}). After 3,000 yr BP, charcoal concentrations were generally higher (mean, 43.1 mg g^{-1}) and major peaks were more pronounced (max., 64.9 mg g^{-1}) and more frequent (3 peaks per 1,000 yr; Fig. 3a and Table 1). Notably, there was no charcoal peak coincident with initial settlement ca. 3,000 yr BP, but there were clear charcoal peaks at 3,200 and 2,800 yr BP.

Average $\delta^{13}C$ values generally increased from 7,000 to 3,000 yr BP, with notable minor peaks between 5,400 and 4,000 yr BP (Fig. 3b). After 3,000 yr BP, $\delta^{13}C$ values were much higher, with prominent peaks at 2,800 and 700 yr BP. Conversion of $\delta^{13}C$ to the percentage of C_4 vegetation by mass balance provides a similar but more easily interpreted record because $\delta^{13}C$ values that were depleted by a closed canopy or wetland effects do not impact this calculation of mean values (Fig. 3c). C_4 grasses were virtually absent from soil carbon pools between 7,000 and 6,300 yr BP but made up a steady minority of vegetation (~5–10%), with peaks in C_4 grasses between 6,200 and 3,600 yr BP and slightly higher abundance after that. The proportion of C_4 grasses more than doubled at 3,000 yr BP, with subsequent peaks between 2,000 and 300 yr BP (Table 1) and reaching highest levels (67% of soil organic carbon) at 700 yr BP.

Discussion

The syntheses of charcoal and $\delta^{13}C$ records from the Sigatoka valley indicate that C_4 grassland patches were present but very limited in distribution and abundance after 6,200 yr BP but before human settlement, consistent with previous palynological studies[27]. However, the pre-Lapita record of fires and C_4 vegetation was dynamic and included small peaks in fire and grassland distribution between 6,200 and 3,000 yr BP, although these peaks were not always synchronous. Our charcoal method quantifies the chemically recalcitrant fraction[35] that is probably biased towards charcoals formed at higher temperatures and in coarser fuels (that is, forest clearing fires) and underrepresents cooler fires in grassy fuels[36]. This may account for the lack of synchrony between the charcoal peaks in forest fires and isotope peaks of grass abundance.

After human settlement, C_4 vegetation and fire both increased in abundance well above pre-Lapita values, but these records were also dynamic. Lapita era (ca. 3,200–2,600 yr BP) grassland expansion is seemingly out of sync with fire activity (Fig. 3c). As noted above, low-temperature charcoals are particularly vulnerable to oxidation[36], so our charcoal records may be biased against low-temperature charcoals, particularly those from existing grassland patches at the time of initial settlement. This lack of synchrony in isotope and charcoal records during the Lapita period might indicate preferential burning by Lapita people within and anchored to existing grassland patches, a form of grass-fallow swidden[11]. By contrast, synchronous peaks in charcoal and expanding C_4 vegetation between 2,800 and 200 yr BP (Table 1) provide evidence of fire activity primarily within forests, promoting the expansion of C_4 grasslands at the expense of forests within the broader Sigatoka landscape. Fire and grasslands were at their highest levels in the past 7,000 yr between 2,800 and 200 yr BP, and C_4 vegetation was at its most abundant in the past 1,700 yr, indicating a clear anthropogenic effect after settlement and with economic intensification, as noted by others[2,11].

A similar pattern was identified by (ref. 37) using radiocarbon-dated charcoal from Sigatoka area alluvium to track fire activity (Fig. 4a). One radiocarbon date calibrated to 5,500–5,100 yr BP, indicating the presence of forest fires before human settlement. The remaining nine dates are post-Lapita, falling between 2,900 and 300 yr BP. Sixty percent of the dates fall within the past 1,500 yr.

Table 1 | Timing of peaks in fire or grassland vegetation at multiple scales and relationships to El Niño frequencies, percentage of sand at El Junco in the Galapagos Islands and WPWP wildfires and droughts

	Fire and vegetation records					Climate/Drought records		
Peak date BP	Sigatoka fire	Sigatoka grasses	Sigatoka ^{14}C (ref. 37)	Fiji, Vanuatu, New Caledonia (Global Charcoal Database)	Palau (Global Charcoal Database)	Laguna Pallcacocha El Niños	El Junco sand	WPWP fire and drought
6000		X						
5600	**X**					**X**		
5400	**X**	**X**	**X**	**X**				**X**
4800	**X**					**X**		**X**
4600		**X**						**X**
4400		**X**						**X**
4300	**X**			**X**				**X**
4100					X			
3900		**X**					**X**	
3700	**X**			**X**				**X**
3600	**X**	**X**						**X**
3200	**X**							**X**
3000				**X**		**X**		
2900		**X**			**X**	**X**		
2800	**X**		**X**			**X**		**X**
2700	**X**	**X**		**X**				**X**
2400					**X**			**X**
2300	**X**			**X**			**X**	**X**
2000	**X**	**X**		**X**			**X**	
1900					**X**		**X**	
1700	**X**	**X**		**X**		**X**	**X**	**X**
1400	**X**	**X**				**X**		
1000				**X**		**X**		**X**
900	**X**	**X**			**X**	**X**	**X**	
700	**X**	**X**	**X**			**X**	**X**	**X**
500				**X**		**X**		**X**
300		**X**	**X**	**X**		**X**		**X**
200	**X**							**X**
100					**X**		**X**	

El Niño frequencies were inferred from Laguna Pallcacocha, Ecuador[12]. Percentage of sand at El Junco in the Galapagos Islands are from (ref. 45) and WPWP wildfires and droughts are from (ref. 21). Bolded text indicate fire/grass episodes that correspond to droughts.

Major features of this pattern are present at multiple scales in the Global Charcoal Database[6,38] across Remote Oceania, although their relationship to climate has largely been unappreciated. In fire records across Fiji, Vanuatu and New Caledonia ($N = 16$ palaeofire sites), charcoal was generally low but increasing between 7,000 and 3,200 yr BP, with minor peaks between 5,400 and 3,700 yr BP (Figs. 4b and 5a and Table 1). Charcoal began increasing rapidly at 3,200 yr BP, with subsequent peaks between 3,000 and 300 yr BP. Charcoal was at its highest levels in the past 1,700 yr. On Palau in Micronesia ($N = 7$ palaeofire sites; Fig. 5a,b), charcoal was generally low from 7,000 to 3,200 yr BP, with a minor peak at 4,100 yr BP. Charcoal increased from 3,200 yr BP, with peaks between 2,900 and 100 yr BP. Charcoal was at its highest levels between 2,000 and 700 yr BP.

The major patterns of these records generally corroborate previous interpretations that fire and grasslands were rare but present before human settlement between 3,200 and 2,900 yr BP (ref. 39), and that charcoal and deforestation increased dramatically upon settlement by Lapita people[2,9,40]. However, embedded within these records is evidence for strong climate influence, both before and after human settlement, that has been previously unrecognized (Fig. 5). In the Sigatoka valley, nearly all peaks in fire activity or grassland expansion (95%) correspond with either drought-related wildfires in Borneo (70%, particularly for the pre-settlement period) or high frequencies of El Niño proxies from Laguna Pallcacocha[12] and El Junco in the Galápagos[15] (55%; Table 1). Similar patterns are evident (Table 1) in the Sigatoka alluvial charcoal dating (80% associated with droughts), in the Fiji, Vanuatu and New Caledonia peaks in fire (100%), as well as in the Palau peaks in fire activity (83%). This pattern implicates a strong influence of decadal to centennial-scale climate variation and severe drought on the deforestation of Remote Oceanic islands via fire after human settlement. The addition of human ignitions, especially from swidden agriculture, amplified the impacts of drought on deforestation after Lapita settlement but was not the exclusive driver of this fire activity. Land-use amplification of ENSO and drought signals is seen in palaeofire records from tropical forests elsewhere in the world[41,42].

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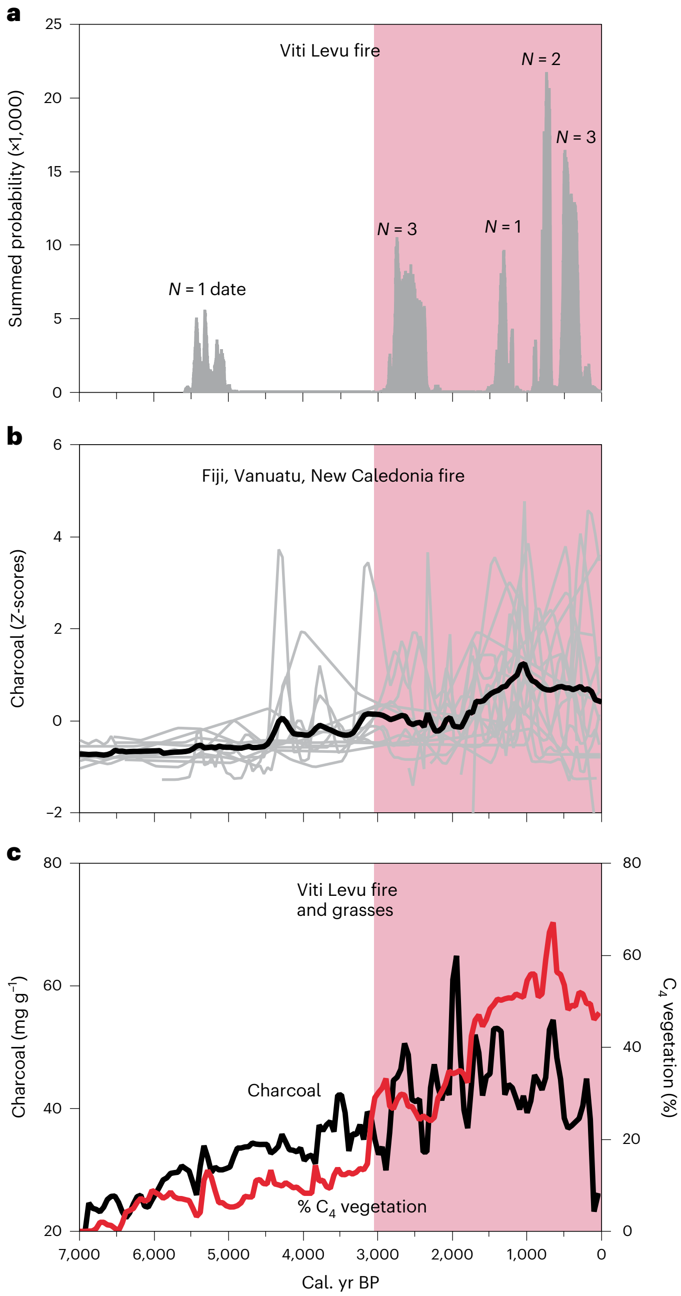

Fig. 4 | Comparison of Sigatoka records with regional fire records. a, Summed probability distribution of alluvial charcoal dates from (ref. 37) (grey areas). **b**, Synthesis of charcoal concentrations from the Global Charcoal Database for Fiji, Vanuatu and New Caledonia (black line; thin grey lines indicate individual records). **c**, Syntheses of charcoal (black line) and C_4 vegetation (red line) from the Sigatoka coring programme.

The Fiji pattern may be visible but also previously unrecognized in other noteworthy Remote Oceanic records, including fires before human settlement between 5,000 and 3,500 yr BP, followed by increased charcoal after 3,000 yr BP and greatest fire activity after 1,700 yr BP in Samoa[43], Guam[40] and the Solomon Islands[44]. Reconstructions of El Niño activity for the early and middle Holocene (11,000–5,000 yr BP) are sometimes contradictory, but modern El Niño patterns are most often identified as having established at low frequencies between 6,000 and 3,000 yr BP and increasing frequencies after 3,000 yr BP (refs. 12,13,15,45). The fire records from Remote Oceania surveyed here largely conform to this pattern: low-frequency peaks (and low charcoal concentrations) between 6,000 and 3,000 yr BP, followed by increasing frequencies of fire peaks (and charcoal values) in the past 3,000 yr. In the Laguna Pallcacocha record[12], El Niño proxy events were at their highest frequencies in the entire Holocene for the period from 1,700 to 100 yr BP, with an average of more than 12 El Niño events per century. This is precisely the period when Sigatoka C_4 vegetation and regional fire activity were at their highest (Fig. 5). In our dataset from Viti Levu, frequent El Niños are not the only drought record that correlated with charcoal and C_4 vegetation peaks; in combination with hydrological droughts associated with the WPWP, particularly in the pre-settlement period, climate events correlated with nearly all peaks in fire activity and grass expansion in the Sigatoka valley and across the region (Table 1).

Lightning is not uncommon on Viti Levu and other large islands. Viti Levu averages 0.8 cloud-to-ground lightning flashes km^{-2} yr^{-1} (compared with 0.5 flashes km^{-2} yr^{-1} in the Sierra Nevada of California[46]), with the greatest lightning density occurring in the Sigatoka valley region[47]. Lightning is most common during the wet season (November–April) but occasionally occurs during the winter dry season (May–October). El Niño typically reduces September–May precipitation in Fiji, Vanuatu and New Caledonia[48], when lightning would typically be most abundant. Charcoal evidence in Fiji and elsewhere in Remote Oceania indicates that lightning and drought were sufficient to allow fires to start and spread long before human settlement. However, the magnitude of charcoal abundance and the frequencies of charcoal peaks unquestionably expanded with the introduction of anthropogenic burning in the Lapita period, even well inland from the earliest dated settlements (at least 70 km upriver from the coast). The magnitude of burning and landscape change after 3,000 yr BP cannot be understood without reference to land-use history. However, previous interpretations of landscape degradation in Remote Oceania have overemphasized the responsibility of human activities and overlooked the impact of climate. It is clear from Remote Oceania and varied other contexts that land use can amplify the impacts of climate variation on fire activity[41,42,49]—an environmental lesson that may be even more salient to the contemporary world. Problematizing human responsibility in Pacific environmental change requires us to reconsider the type of environmental lessons to be drawn from Oceanic historical ecology, including narratives of resilience and adaptation[50,51].

Pacific islands have been natural laboratories for identifying the character of feedbacks between grass and fire that enable tropical grasslands to spread once established[24,52]. Grasses are inherently more flammable than woody vegetation and grasslands create warmer, drier microclimates with stronger winds that facilitate fire spread[53]. For traditional farmers in Remote Oceania, slash-and-burn farming has been a viable dryland farming technique for millennia, but grass-covered fallows effectively enable further deforestation via the grass–fire cycle. This has happened in the past with pyrophyllic native grasses, such as *Imperata cylindrica*[54], and is accelerated today with the introduction of invasive grasses, such as *Pennisetum polystachion*[24,52]. As we document here, droughts triggered by El Niño seem to have acted as a catalyst for grass–fire cycle deforestation in the past. Models predict that chronic El Niño-like conditions may characterize the next century of climate change in the region[55], in which case Oceanic islands may become more vulnerable to the further loss of forest cover due to the grass–fire cycle.

Methods

In July 2013, we conducted landscape geoarchaeology fieldwork in the Sigatoka valley. We focused on watersheds of tributaries to the Sigatoka River to ensure that sedimentary proxies, including charcoal and soil organic carbon, would be localized and spatially explicit rather than driven by the complex history of transport and storage within the Sigatoka River alluvium. Watersheds for analysis were selected because of their proximity to archaeological sites that had previously been radiocarbon dated[29]. Coring locations were selected from an approximate midpoint in the alluvial deposits of the watershed to primarily

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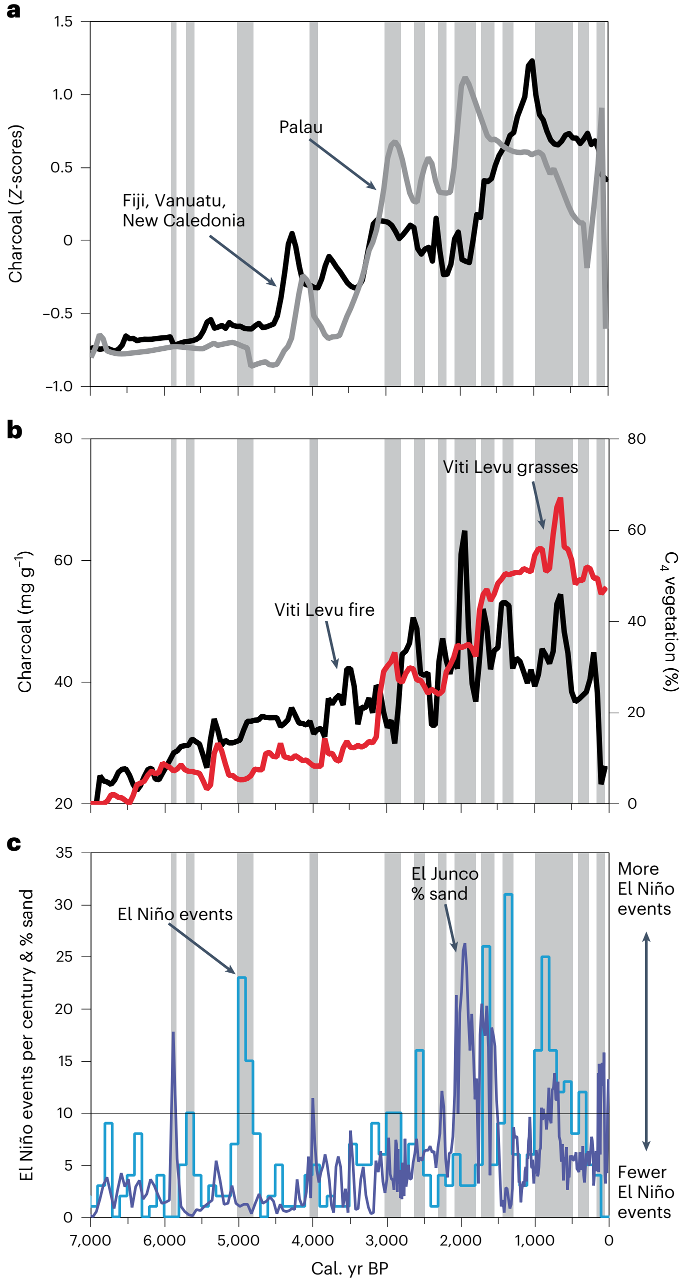

Fig. 5 | Comparisons of Fiji and regional fire records with El Niño reconstructions. a, Plots of fire activity from the Global Charcoal Database from Palau, Fiji, Vanuatu and New Caledonia. **b**, Charcoal (black, left axis) and C_4 vegetation (red, right axis) from the Sigatoka valley coring programme. **c**, El Niño reconstructions from Laguna Pallcacocha (light blue line) and El Junco (purple line). Grey bars in all plots indicate periods of frequent El Niño events defined as ≥10 events per century at Laguna Pallcacocha and ≥10% sand in the El Junco record.

capture tributary overbank flooding deposits without influence of flood deposits from the Sigatoka River or colluvium from the valley margins. Each locality was cored with a 3-cm-diameter percussion corer up to ~5–6 m depth. Except at Tuwalu, cores did not refuse on coarse lag or bedrock, but coring extensions were exhausted, indicating thick (>6 m deep) post-glacial tributary alluvium. Cores were collected in 90-cm copolyester sleeves for later description and sampling. Two paired cores ~25 cm apart were collected from each locality to increase the amount of soil/sediment sampled and to increase the visibility of stratigraphy for accurate description and measurement of soil and lithostratigraphic properties.

Extracted cores were opened as pairs at a field base camp, measured using extracted depths (cm recovered below surface) and described using standard nomenclature for colour, texture, structure and pedofeatures[56]. Described cores were photographed and subdivided in 5-cm increments or at stratigraphic boundaries and double bagged for shipment to the Environmental Archaeology Lab at Southern Methodist University (SMU) under a US Department of Agriculture Foreign Soil Import permit to C.I.R. This produced 97 samples at Caluwe, 97 samples at Caqasi, 142 samples at Qaraqara and 64 samples at Tuwalu.

At SMU, gravel abundance (>2 mm weight %) was measured by dry screening, and 10 g each from adjacent samples were used to estimate grain-size proportions of <2 mm sediments/soils using a wet-sieving and pipette method[57]. Sample pH was measured in a 1:1 slurry with deionized water. Organic matter and charcoal were both measured by mass using an HNO_3 digestion-loss-on-ignition method[35,58]. Samples with >3% gravel were excluded from the charcoal records as being unsuitable for charcoal preservation. Sample fractions <125 µm were decalcified with 3 N HCl and measured for stable carbon isotopes at the Center for Archaeology, Materials and Applied Spectroscopy at Idaho State University. The percentage of C_4 vegetation contributing to the soil carbon pool by mass was calculated, assuming a $\delta^{13}C$ of −25‰ for C_3 vegetation and −12‰ for C_4 vegetation. Negative percentages of C_4 for individual localities (that is, $\delta^{13}C < -25‰$ because of canopy or wetland depletion effects on C_3 vegetation) were converted to 0% since C_4 vegetation cannot occupy negative space. Basic data processing was done in Excel 16.75.2.

Charcoal macrofossils of sufficient size and preservation for radiocarbon dating were rare, so most radiocarbon dates were done on bulk soil fractions <2 mm that were pretreated with hot 78% HNO_3, followed by hot 3 N HCl to digest unburned organics, remove carbonates and isolate charcoal in the carbon pool (Extended Table 1). Because accelerated hillslope erosion adds old carbon to sedimentary basins[59], older radiocarbon dates out of sequence with other dates were excluded from consideration. Remaining radiocarbon dates were all calibrated using SHCal 20 (ref. 60) and used to build age–depth models using the R package CLAM (2.2)[61]. In the CAL core, a clear hiatus was identified in the lithology and in the radiocarbon data, so this was included in the model[11]. Although buried soils indicate some periods of stability in the cores at other localities, the radiocarbon data indicated more-or-less continuous sedimentation rates between dated deposits and were modelled as continuous age–depth relationships (Extended Data Figs. 6–10).

For the current analysis, charcoal, $\delta^{13}C$ and percentage of C_4 vegetation were binned at 50-yr intervals using annually weighted averages of the original down-core values. This facilitated (1) synthesis across core localities by averaging Sigatoka-wide values for each 50-yr bin and (2) comparisons with climate reconstructions that are largely at the centennial scale. This is also a better reflection of the inherent uncertainty of the radiocarbon age–depth models. Standardized charcoal records for all sites in Remote Oceania were extracted from the Global Charcoal Database (http://www.paleofire.org). Charcoal sites from the Solomon Islands were excluded because El Niño impacts differ here from our other Remote Oceania sites. Charcoal from the Mago Island site was excluded because of the poor quality of the chronology for this site. These records were also binned at 50-yr intervals for synthesis and comparison. Charcoal and C_4 vegetation peaks were defined as simple mathematical peaks in which *y* values were higher than neighbours on both sides up to 100 yr (two samples) in each direction. Radiocarbon dates from (ref. 37) were calibrated using SHCal 20 (ref. 60) with the originally published radiocarbon data.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

 https://doi.org/10.1038/s41559-023-02212-8

Data availability

All stratigraphic data presented in the main text and in Extended Data figures are available as Supplementary Data and via Figshare at https://doi.org/10.6084/m9.figshare.23989998.

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Author contributions

C.I.R., J.S.F. and J.V.D. conceptualized the project, acquired funding and conducted investigations. C.I.R. curated data, conducted formal analysis, developed the methodology, administered the project together with J.S.F., performed visualization and wrote the original draft of the manuscript. All authors reviewed and edited the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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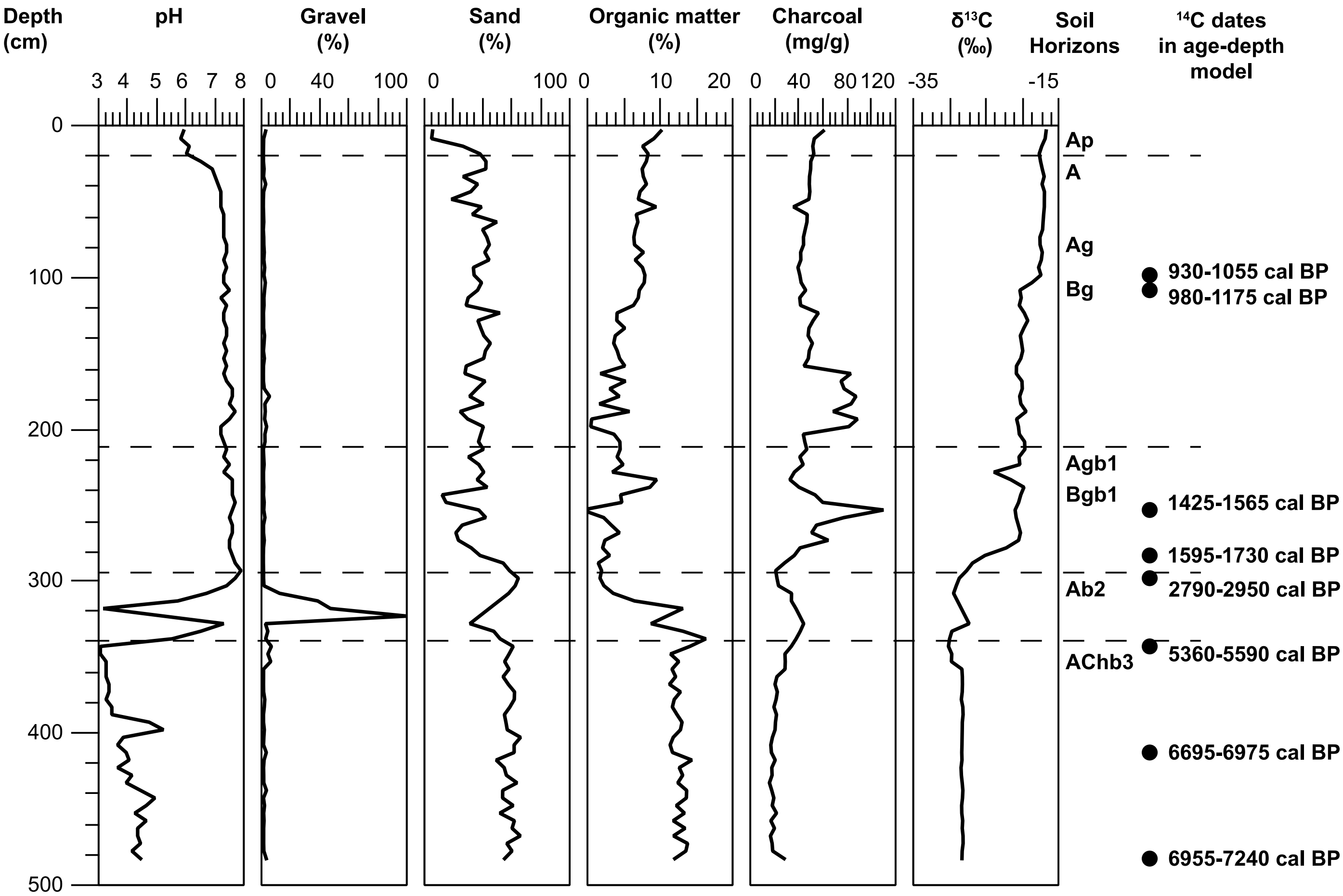

Extended Data Fig. 1 | Stratigraphic data for the Caluwe core. Stratigraphic data for the Caluwe Creek locality (CAL). Calibrated radiocarbon dates shown are only those used in the age depth model (Extended Data Fig. 6).

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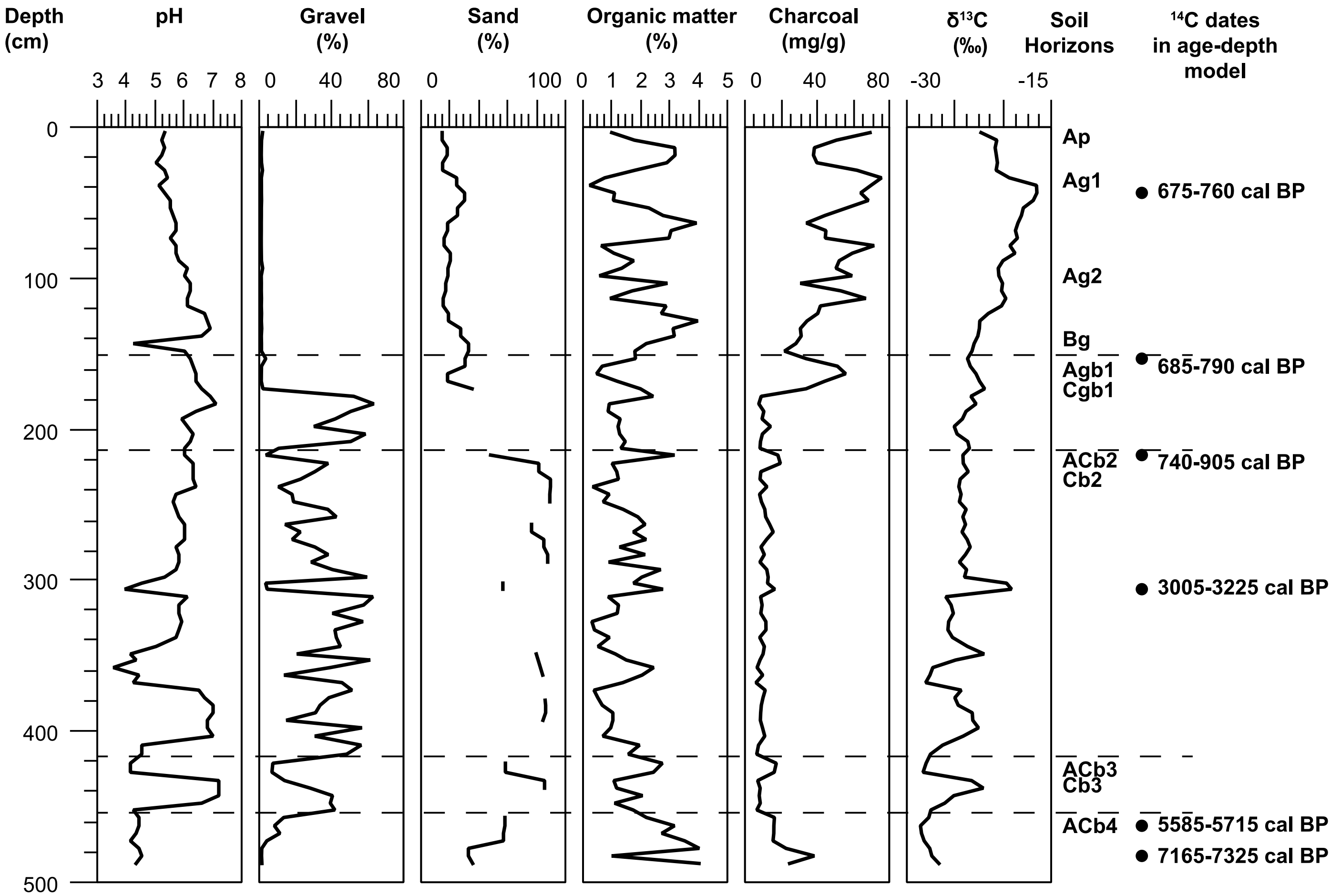

Extended Data Fig. 2 | Stratigraphic data for the Caqasi core. Stratigraphic data for the Caqasi Creek locality (CAQ). Calibrated radiocarbon dates shown are only those used in the age depth model (Extended Data Fig. 7).

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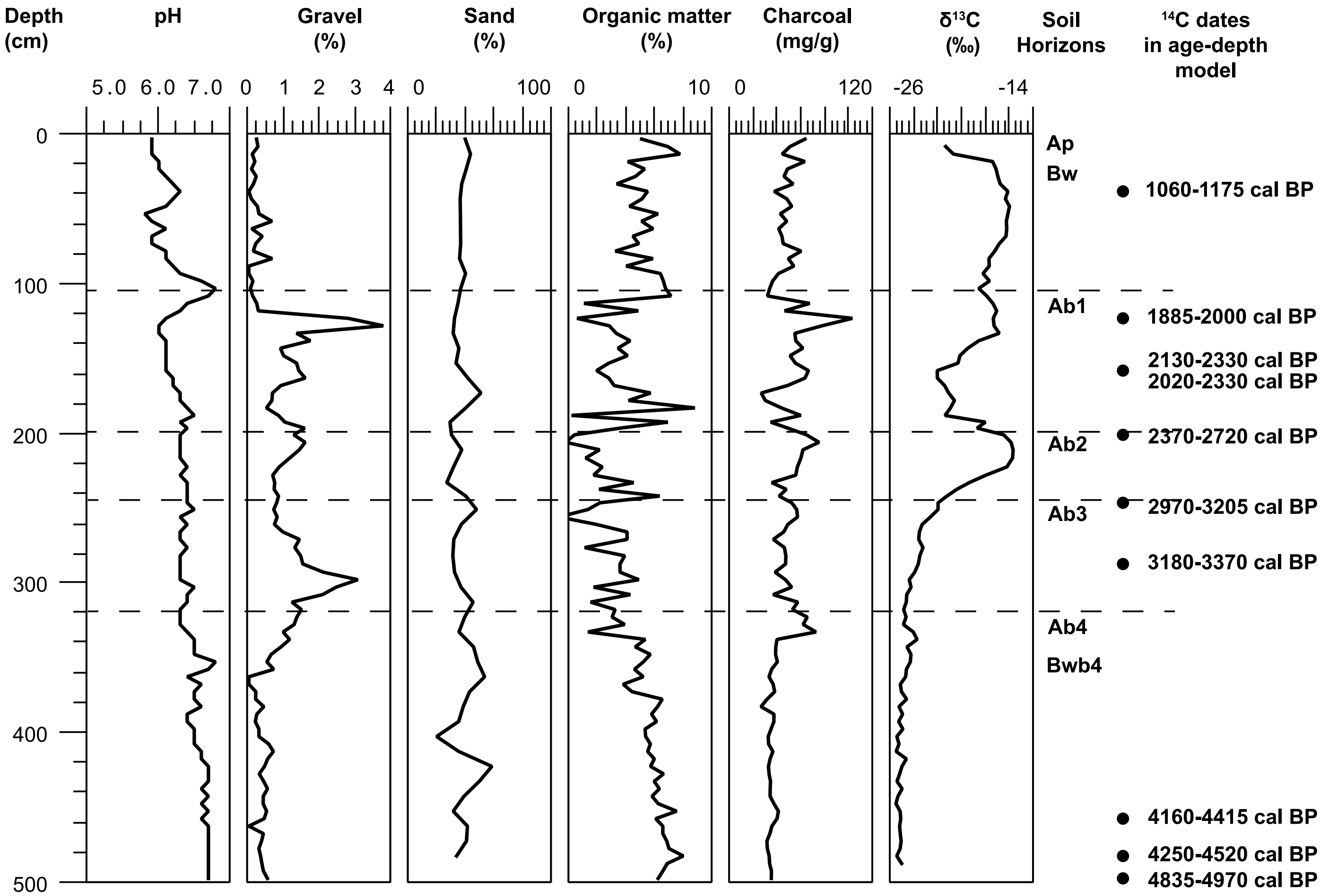

Extended Data Fig. 3 | Stratigraphic data for the Qaraqara 1 core. Stratigraphic data for the Qaraqara Creek locality 1 (QAR 1), the older alluvial terrace. Calibrated radiocarbon dates shown are only those used in the age depth model (Extended Data Fig. 8).

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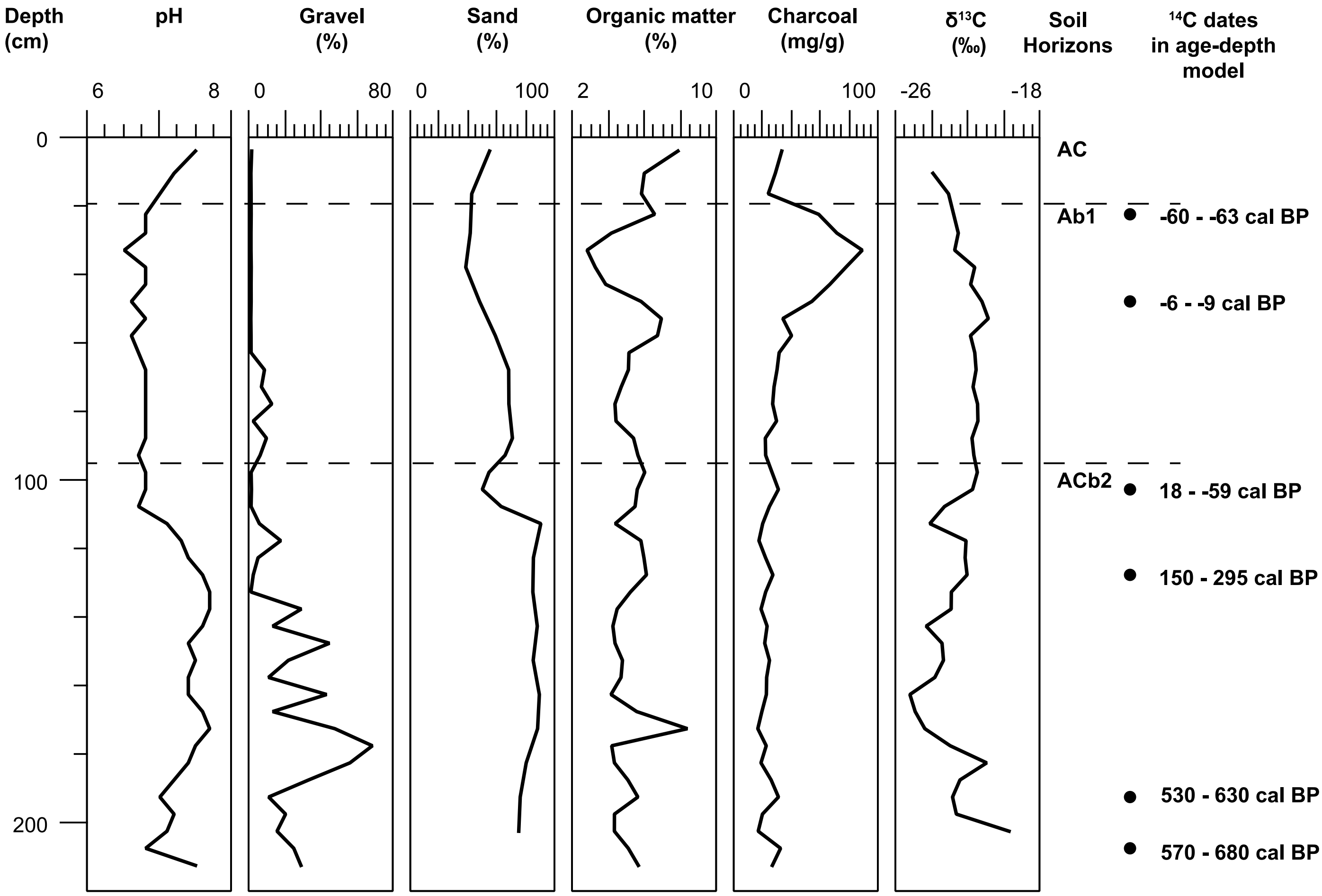

Extended Data Fig. 4 | Stratigraphic data for the Qaraqara 4 core. Stratigraphic data for the Qaraqara Creek locality 4 (QAR 4), the younger alluvial terrace. Calibrated radiocarbon dates shown are only those used in the age depth model (Extended Data Fig. 9).

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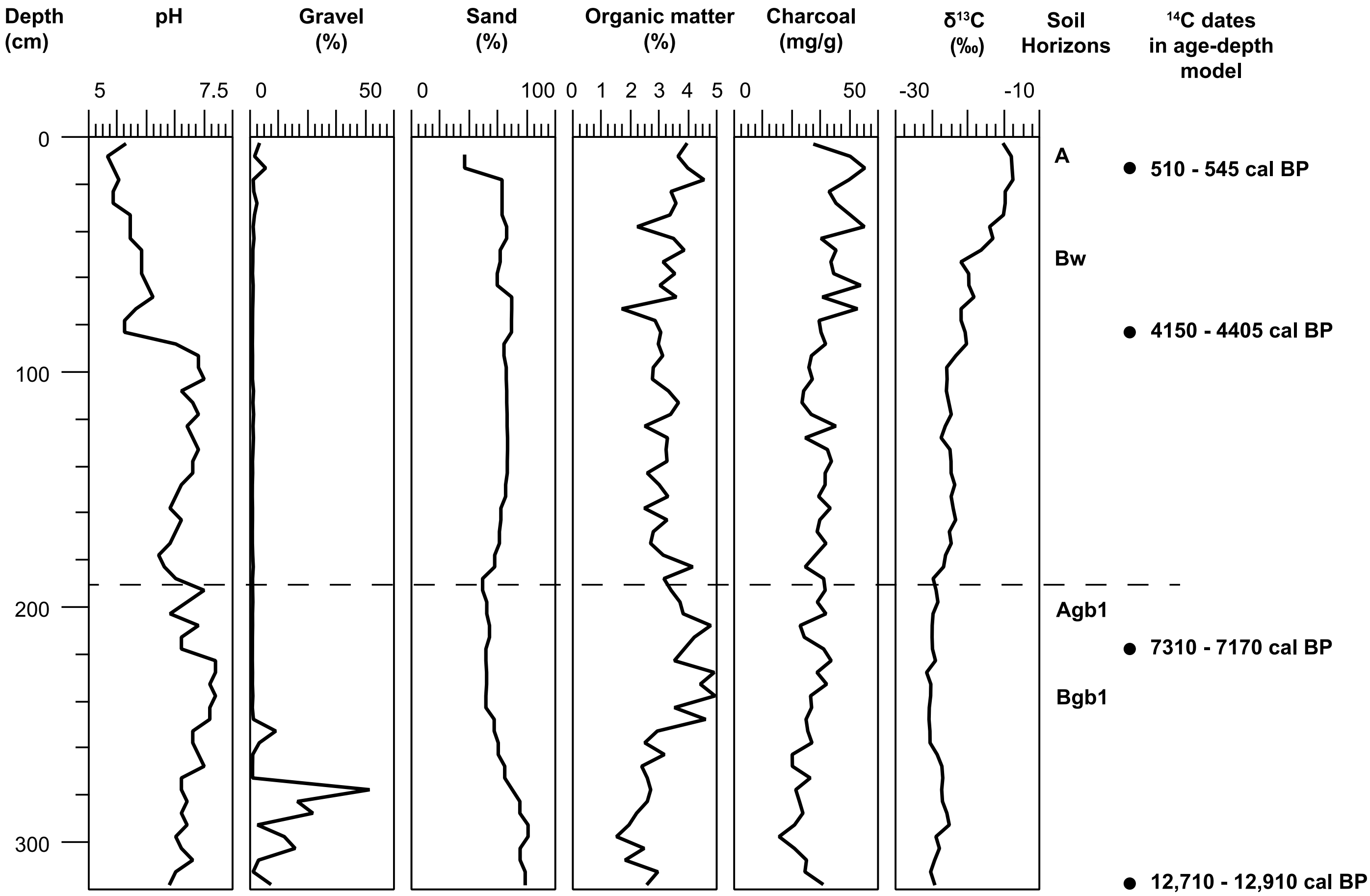

Extended Data Fig. 5 | Stratigraphic data for the Tuwalu core. Stratigraphic data for the Tuwalu Creek locality (TUW). Calibrated radiocarbon dates shown are only those used in the age depth model (Extended Data Fig. 10).

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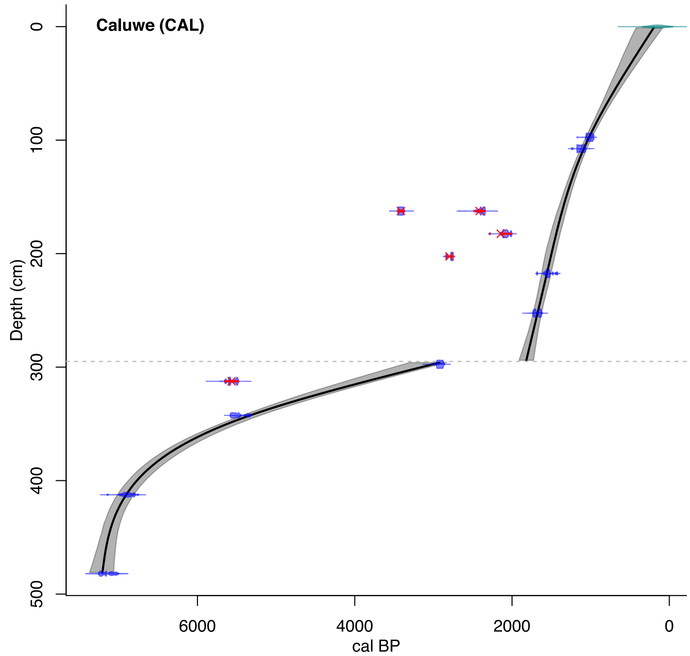

Extended Data Fig. 6 | Age-depth model for the Caluwe Creek locality (CAL). Calibrated ages used in the model are in blue. Calibrated ages for reworked, older, rejected dates are in red. A post-bomb date from the plowzone is not shown. Neither is a radiocarbon infinite date on charcoal from the Ab1 soil as it could not be plotted at this scale. Error lines indicate 95% confidence interval (CI) calibrated dates. Rectangles indicate 68% CI calibrated date ranges.

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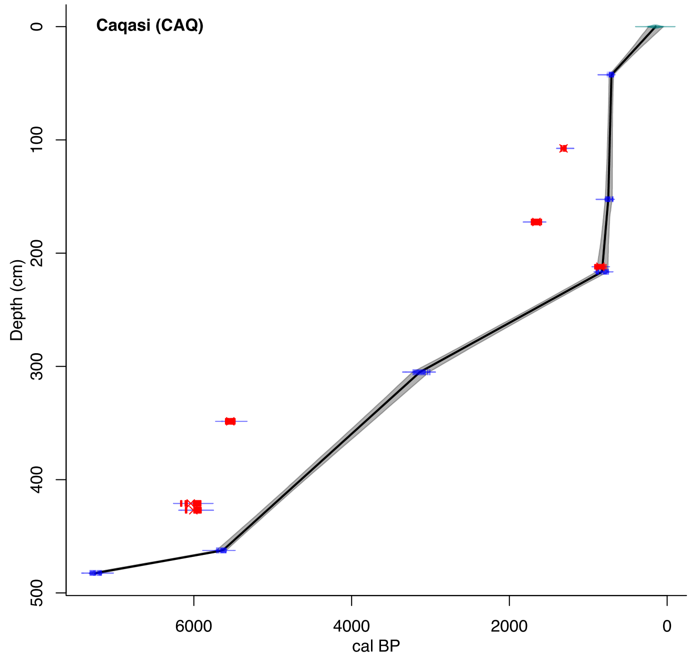

Extended Data Fig. 7 | Age-depth model for the Caqasi Creek locality (CAQ). Calibrated ages used in the model are in blue. Calibrated ages for reworked, older, rejected dates are in red. Error lines indicate 95% confidence interval (CI) calibrated dates. Rectangles indicate 68% CI calibrated date ranges.

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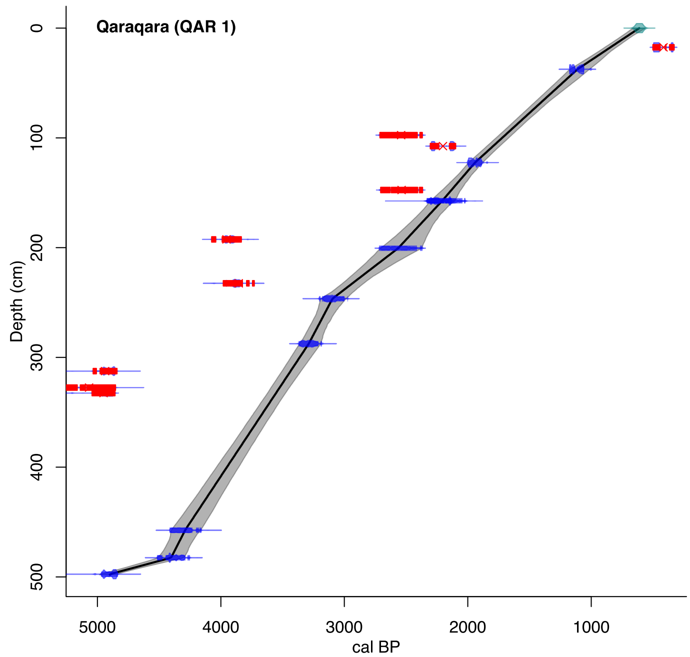

Extended Data Fig. 8 | Age-depth model for the Qaraqara Creek locality 1 (QAR 1), the older alluvial terrace. Calibrated ages used in the model are in blue. Calibrated ages for reworked, older, rejected dates are in red. Error lines indicate 95% confidence interval (CI) calibrated dates. Rectangles indicate 68% CI calibrated date ranges.

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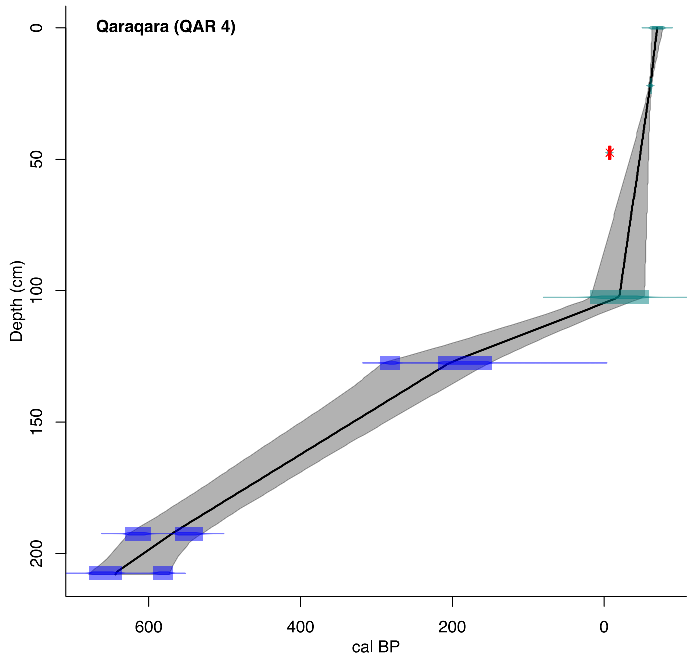

Extended Data Fig. 9 | Age-depth model for the Qaraqara Creek locality 4 (QAR 4), the younger alluvial terrace. Calibrated ages used in the model are in blue. Calibrated ages for reworked, older, rejected dates are in red. Error lines indicate 95% confidence interval (CI) calibrated dates. Rectangles indicate 68% CI calibrated date ranges.

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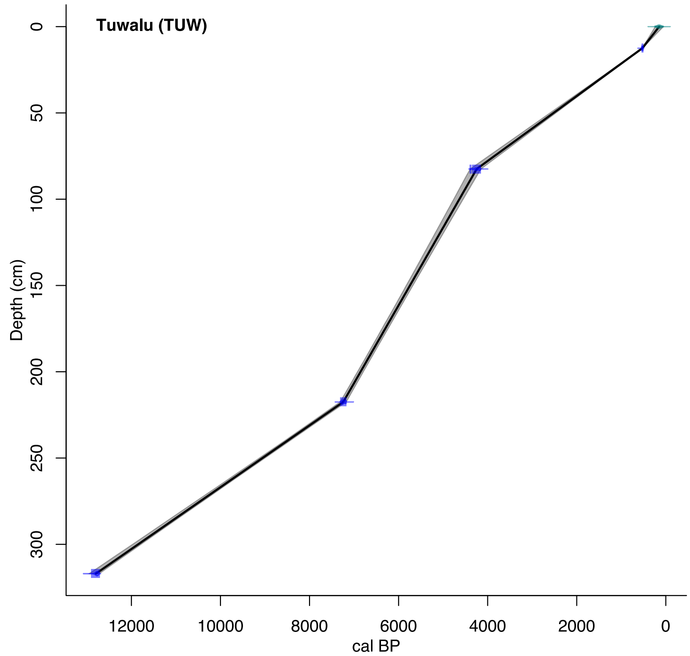

Extended Data Fig. 10 | Age-depth model for the Tuwalu Creek locality (TUW). Calibrated ages used in the model are in blue. Calibrated ages for reworked, older, rejected dates are in red. Error lines indicate 95% confidence interval (CI) calibrated dates. Rectangles indicate 68% CI calibrated date ranges.

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☒	☐	Estimates of effect sizes (e.g. Cohen's *d*, Pearson's *r*), indicating how they were calculated

Our web collection on statistics for biologists contains articles on many of the points above.

Software and code

Policy information about availability of computer code

Data collection	Data processing was done in Excel 16.75.2
Data analysis	50-year weighted averages were calculated in Excel. Radiocarbon calibration was done using the CLAM v2.2 package in R.

For manuscripts utilizing custom algorithms or software that are central to the research but not yet described in published literature, software must be made available to editors and reviewers. We strongly encourage code deposition in a community repository (e.g. GitHub). See the Nature Portfolio guidelines for submitting code & software for further information.

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We have made every effort to get the stratigraphic data available via Neotoma Database but DOI are still not available. I am continuing to work on this but in the meanwhile I have included all of the data as a Supplementary Information Excel file and changed the data availability statement to the following (with approval from Luiseach Nic Eoin: "All stratigraphic data presented in the main text and in Extended Data figures are available as a Supplemental Data file accompanying this paper."

Human research participants

Policy information about studies involving human research participants and Sex and Gender in Research.

Reporting on sex and gender	Sex and gender information were not collected and are not part of this study.
Population characteristics	This study does not involve human populations.
Recruitment	This study does not involve human populations.
Ethics oversight	Since this study does not involve human participants, this is not subject to an IRB.

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Ecological, evolutionary & environmental sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description	This is a paleoecological study of deep soil cores from a transect of small watersheds that are tributary to the Sigatoka River on Viti Levu, Republic of Fiji. We analyzed charcoal content and stable carbon isotope ratios to reconstruct fire and vegetation histories.
Research sample	Samples were of soil and sediment from cores taken in alluvial deposits from small watersheds tributary to the Sigatoka River to ensure that sediments were derived from the surrounding hillslopes and not reworked from long-term storage in Sigatoka River alluvium.
Sampling strategy	Samples were collected every 5 cm continuously down cores, unless clear sedimentary boundaries were encountered. All samples were analyzed for charcoal and stable carbon isotopes, unless there was too little fine (< 2 mm) sediment.
Data collection	3 cm diameter percussion cores were collected in the field in 91 cm segments and repeated with ~25 cm horizontal spacing for paired core holes. Paired core segments were opened, described and subsampled at 5 cm intervals at the field camp.
Timing and spatial scale	Cores were collected in July 2013 from within a portion of the Sigatoka Valley representing roughly 130 km2.
Data exclusions	Sediment samples with > 3% gravel were excluded from charcoal analysis because the depositional energy was too high for charcoal deposition. Sections with < 3% gravel had to be at least 10 cm thick to be included in the analysis.
Reproducibility	Sections of QAR 1 and CAL 1 were measured for charcoal multiple times to assess reproducibility.
Randomization	Samples were organized into Pre-Lapita (> 3000 BP) and Lapita/Post-Lapita (< 3000 BP) based on interpolated age-depth models.
Blinding	Blinding was not possible or relevant in our study. All samples were measured for charcoal and stable carbon isotopes before the radiocarbon chronology was complete, so we did not know which chronological category fell into until after analysis.

Did the study involve field work? ☒ Yes ☐ No

Field work, collection and transport

Field conditions	Coring was performed during the Austral winter. Coring conditions were sunny or partly cloudy with little wind, warm temperatures, and no precipitation.
Location	Locality Lat Long CAL -18.145656 177.52127 CAQ -18.077592 177.5444 QAR -17.982554 177.629438 TUW -17.874397 177.80771

Access & import/export	We solicited and recieved permission from both the national government (through the Fiji Museum), local governments (Nadroga-Navosa Province), and from local Ratu (chiefs) with authority over local land use. I had previously secured a US Department of Agriculture permit for the importation of foreign soils from Fiji to my lab at Southern Methodist University.
Disturbance	Coring only left two 3 cm diameter holes in the ground, although foot traffic during coring disturbed the surface around 5-10 m2. Coring was only done in settings that were not in active cultivation to minimize disturbance for local subsistence farmers.

Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

Materials & experimental systems

n/a	Involved in the study	
☒	☐	Antibodies
☒	☐	Eukaryotic cell lines
☐	☒	Palaeontology and archaeology
☒	☐	Animals and other organisms
☒	☐	Clinical data
☒	☐	Dual use research of concern

Methods

n/a	Involved in the study	
☒	☐	ChIP-seq
☒	☐	Flow cytometry
☒	☐	MRI-based neuroimaging

Palaeontology and Archaeology

Specimen provenance	This study used locational and chronological data from previous archaeology but did not generate any new collections. Permission was granted by the Fiji Museum, although our work was fundamentally off-site geoarchaeology.
Specimen deposition	Sterilized oil samples that were not consumed in analysis are housed at the Geoarchaeology Lab at Southern Methodist University.
Dating methods	New radiocarbon dates were obtained from bulk soil/charcoal samples at the University of Arizona AMS lab and the UC Irvine Keck AMS lab. These were calibrated with SHCal13 (identical to SHCal 20 in this part of the curve) in CLAM in R.

☒ Tick this box to confirm that the raw and calibrated dates are available in the paper or in Supplementary Information.

Ethics oversight	No ethical guidance was required since this did not involve the disturbance or analysis of archaeological materials.

Note that full information on the approval of the study protocol must also be provided in the manuscript.