Mauritius on fire: Tracking historical human impacts on biodiversity loss

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Title: **Mauritius on fire: Tracking historical human impacts on biodiversity loss**

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Abstract

Fire was rare on Mauritius prior to human arrival (AD 1598); subsequently three phases of elevated fire activity occurred: c. 1630-1747, 1787-1833, and 1950-modern. Elevated fire frequency coincided with periods of high human impact evidenced from the historical record, and is linked to the extinction of island endemics.

Tweetable abstract: A 1000 year charcoal record shows humans brought frequent fire to Mauritius, fire is linked to extinction events #Dodo

Key words: Anthropocene; charcoal; Dodo; ecosystem degradation; extinction; introduced species; islands; habitat degradation; Mare Tatos; sub-tropical

Text

THE ISLAND OF MAURITIUS BORE WITNESS TO PROBABLY THE MOST ICONIC SINGLE ACT OF HUMAN ECOSYSTEM INTERFERENCE OF ALL TIME WHEN, IN AD 1690, THE DODO WAS DRIVEN TO EXTINCTION (Roberts & Solow 2003, Hume *et al.* 2004). Yet the relative importance of the multiple anthropogenic factors responsible for the loss of the Dodo, and other extinctions on Mauritius, remain ambiguous. Prior to the first landing of the Dutch on Mauritius in AD 1598 (all dates hereafter in years AD) the island naturally supported a palm or semi-dry woodland vegetation and was virtually untouched by humans, with the only possible earlier visitors being Arab or Portuguese traders (Cheke & Hume 2008, de Boer *et al.* 2014). Mauritius is therefore an ideal location to explore the role of humans in extinction events because it is a rare case of an island where human impact on ecosystems and written historical records commence simultaneously (Vaughan & Wiehe 1937, Brouard 1963, Grove 1996, Moree 1998, Grihault 2005, Cheke & Hume 2008, Floore & Jayasena 2010, Norder *et al*. 2017).

The Dutch first settled Mauritius 40 years after their initial landings. During the subsequent four centuries the island was occupied and abandoned by the Dutch (1638-1710), French (1721-1810), and British (1810-1968), until it achieved independence in 1968. Since the arrival of humans, Mauritian ecosystems have become degraded through the overexploitation of species for food, the introduction of exotic species (such as rats and cats), and the transformation of the landscape through clearance and agriculture (Brouard 1963, Cheke & Hume 2008, Florens *et al.* 2012, Hume 2013, Florens 2013, Norder *et al.* 2017).

Throughout the centuries, Mauritius has been deforested to harvest timber for construction purposes, to create space for agriculture, and to supply energy for cooking, railways, and the sugar industry. Fire was an integral part of the deforestation process on Mauritius, and consequently charcoal deposited into sedimentary sequences can be used to assess the scale of human impact through time. Here we reconstruct a c. 1000 year fire history from Mauritius, and relate it to historical records of deforestation and demography, species introductions, and extinction events. The integration of empirical palaeoecological data with historically documented events provides a unique insight into the relative impact of the different phases of human activity on Mauritian ecosystems. Although charcoal has been used to track human impacts on tropical island ecosystems elsewhere in the world (e.g. Burney 1987, Premathilake 2006, Rull *et al*. 2015) the unique combination of the Mauritius data with historical records highlights the accuracy with which palaeoecological reconstructions can capture past human impacts.

In 2010, a sediment core was recovered from the Mare Tatos wetland on Mauritius (20^{o} 12’ 44” S, 57^{o} 46’ 22” E, 21 m above sea level) using a Russian corer (de Boer *et al.* 2014). Mare Tatos is located c. 40 km from the site of the first Dutch landings at Port de Warwick (present day Vieux Grand Port). Five radiocarbon dates indicate the upper 100 cm of the Mare Tatos core represents sediments that were deposited during the last c. 1000 years (Table 1). The most probable chronology for the core was established using the ShCal13 and post bomb radiocarbon calibration curves (Hogg *et al.* 2013, Hua *et al.* 2013, Reimer *et al.* 2013) with Bacon source code (Blaauw & Christen 2011) in R (Version 3.2.2; R Core Team 2015) (Fig. 1a).

We extracted 46 samples from the Mare Tatos core for macro-charcoal analysis. For each sample, charcoal particles were identified using standard laboratory procedures (Whitlock & Larsen 2001). Two size fractions of charcoal fragments were quantified (75-160 μm and >160 μm); particle counts for both size fractions, and additionally surface area for particles >160 μm. The smaller size fraction represents fires in the landscape (10's of km), while the larger size fraction reflects fires at the study site (Clark & Patterson 1997). Area calculations were made for the larger fraction to standardise charcoal particle size relative to abundance. Periods of high, landscape scale, fire frequency were classified as "fire zones" when the number of small particles (75-160 μm) per cubic centimetre exceeded 20% of the maximum value (1093 particles/cm^3). Fire was assumed to be virtually absent from the ecosystems when the number of particles dropped below 5% of the maximum values at the landscape (75-160 μm), and local (>160 μm) scales (Kelly *et al.* 2011). Data were plotted using C2 version 1.7.2 (Juggins 2005).

The charcoal data from Mare Tatos indicate three fire zones: (1) c. 1630-1747; (2) c. 1787-1833; and (3) c. 1950 to modern (Fig. 1a). The three fire zones coincide with periods of increasing human impact on Mauritius inferred from historical maps and documented population growth (Fig. 1). Fire frequency and abundance sharply increased after the first colonization of Mauritius by the Dutch, and peaks around the transition between Dutch and French governances (fire zone 1). After an initial peak in fire activity, during most of the French governance, fire activity remains low. The second fire zone, between c. 1787 and 1833, commences during the latter stages of the French governance with the expansion of sugar cane agriculture, and includes the arrival of the British and the industrialisation of agriculture (Norder *et al.* 2017).

During much of the British governance fire activity remained low. The third fire zone, c. 1950 to modern, is broadly coincident with the destruction of forest remnants, and diversification of the economy following independence.

Our data suggest that for c. 500 years prior to the arrival of the Dutch on Mauritius, very little fire activity occurred at Mare Tatos, or within the surrounding landscape (Fig. 1a). The rarity of pre-human fire is concordant with a c. 8000-year reconstruction of micro-charcoal (c. 200 year between samples) from Mare Tatos (de Boer *et al.* 2014). Fire became a major element of the landscape only after the Dutch settled the island, which supports previous assertions that there were no significant landings of people on Mauritius prior to the arrival of the Dutch (Cheke & Hume 2008, Floore & Jayasena 2010).

The first period of elevated fire activity on Mauritius (fire zone 1; c. 1630-1747) is coincident with the first Dutch settlement on the island. Despite a population of just a few hundred people, the charcoal signal evidences fire occurring at both regional (<160 μm) and local (>160 μm) scales (Fig. 1a). The charcoal record detects fires reflecting early clearance and cultivation in the bay area just c. 5 km north-west and south-east of Mare Tatos (Floore & Jayasena 2010; Fig 1b, 1685 map). During fire zone 1 forests were increasingly cut and burnt to provide space to grow crops, such as sugar cane, rice, tobacco, indigo, vegetables and citrus trees (Brouard 1963, Grihault 2005). The peaks and troughs in the local charcoal signal within fire zone 1 could reflect sporadic visits by people to Mare Tatos, possibly related to foraging expeditions and/or selective logging for ebony trees.

During fire zone 1 all large flightless birds on Mauritius became extinct, including Dodo (*Raphus cucullatus*), along with the Raven Parrot (*Lophopsittacus mauritianus*), and two species of endemic giant tortoise (*Cylindraspis inepta* and *C. triserrata*) (Fig. 1a). It is interesting to note that the extinction events lag the first introduction of rats to the island by Arab traders by many hundred years, the subsequent wave of introduced species that occurred with the first Dutch landings by c. 82, 92 and 102 years respectively, and the occupation and introduction of widespread fire by c. 50, 60 and 70 years. The differential duration that species persisted post human arrival attests to the cumulative nature of human impacts, and the species-specific nature of extinction debt (Gaston & Blackburn 1995, Triantis *et al.* 2010). Although it is unlikely that the fire events directly caused extinctions, the data indicates that even localised settlement of humans, their cultivation and burning activities, affected ecosystems in a wider region than the settlements themselves. The destruction of ecosystems (habitat) likely put additional pressure on already stressed wild animal populations.

Once established on Mauritius, the Dutch colonists faced a series of natural (plagues, heavy storm damage) and political (lack of support from the mainland, workers rebellion) difficulties, and abandoned the island in 1710 (Moree 1998). After a decade of practically no human habitation the French settled Mauritius (Cheke & Hume 2008). Fire remained a significant feature of the Mauritian landscape after the governance transition (fire zone 1). The first major lull in fire activity on Mauritius after European colonization occurred between c. 1747-1787, preceding the French revolution (Fig. 1a), when land-based agricultural activities were of minor economic importance compared to the provisioning of goods and services to passing ships (Allen 1989, Addison & Hazareesingh 1999).

The second major increase in fire (fire zone 2; c. 1787-1833) is coincident with an increase of the human population. In 1787 the population was c. 40,000 and grew to c. 60,000 in the 1790's to support the rapidly growing sugar cane industry (Lutz & Wils 1994). Historical archives document the cutting down of vegetation and subsequent burning (Brouard 1963) focused in the northern part of the island near Mare Tatos (Fig. 1b).

A species of endemic fruit bat (*Pteropus subniger*), which roosted in tree hollows and cliffs, went extinct in the wild c. 1795, eight years after the onset of fire zone 2 (Cheke & Hume 2008). The extant fruit bat species on Mauritius (*P. niger*) is currently listed as vulnerable due to habitat loss and hunting (Hutson & Racey 2013, Florens 2015). *P. subniger* was also heavily hunted for food and making torches (Cheke & Hume 2008), but the coincidence of its extinction with the rapid increases in fire (Fig. 1a) suggests that, in addition to predation, habitat destruction may have played a role in its demise.

The major drop in fire activity c. 30 years after the onset of the major expansion in sugar cane area in 1825 is coincident with the projected loss of c. 50% of the natural vegetation on Mauritius (Fig. 1a). By c. 1850 most of the land suitable for sugar cane agriculture on the northern part of Mauritius had been cleared, leaving no natural vegetation left to burn (Fig. 1b, 1872 map). Management of the land for sugar cane from 1833-1950 has left no significant charcoal record despite the practice of a seasonal burning of the fields (Lalljee & Facknath 2008). The absence of a charcoal (fire) signal likely reflects a shift from burning woody vegetation to burning crop stubble (grass), because non-woody vegetation tends to produce less charcoal (Whitlock & Larsen 2001).

It is not until the time of independence that fire activity again increased (c. 1950). Fire zone 3 reflects the transition to the current situation of c. 98 % loss of natural vegetation on Mauritius. The elevated charcoal at Mare Tatos in recent times likely reflects the burning of woody material brought into the area by humans, possibly harvested elsewhere on the island, as by this point little local natural vegetation remained (Fig. 1b). In the last decades, island wide degradation of ecosystems is mainly linked to growing human populations, and an increase in tourism and textile industries (Ramessur 2002).

The fire history from the Mare Tatos wetland was able to precisely detect the documented phases of human arrival, occupation, abandonment, governance and demographic change. Our finding adds weight to inferences made in the absence of corroborating historical evidence that elevated charcoal (fire) on other tropical islands indicates the arrival of human populations (e.g. Burney 1987, Premathilake 2006, Rull *et al*. 2015). The Mare Tatos fire record supports the assertion that, prior to 1598, there was no human occupation of Mauritius. If a conservation goal on the island is to restore ecosystem processes to a pre-human state then fire management is consequently key.

During c. 500 years of human occupation the ecosystems of Mauritius were degraded through forest fragmentation, fires, introduction of exotic species, and overexploitation of natural resources (Cheke & Hume 2008, Rijsdijk *et al.* 2011, Florens *et al.* 2012, Rijsdijk *et al.* 2015). Our research reveals that many extinction events (including Raven parrot, Dodo, giant tortoise and fruit bat) over the last 500 years on Mauritius occurred during the periods of elevated human activity indicated by frequent fire events recorded in the Mare Tatos sediments (Fig. 1a). All of these species had suffered significant environmental pressures in the past, such as major drought events, and survived (de Boer *et al.* 2015). Yet within c. 50 years of human occupation, and the introduction of frequent fire events, the extinctions had begun (Fig. 1a). The timings of the individual extinction events highlights the high sensitivity of taxa to human activity, and the species-specific response to fire and habitat loss. The coincidence of the greatest species loss with the first period of elevated fire likely reflects the wide-ranging and high-level human interference on Mauritius during this period. The reconstructed fire history of Mauritius suggests that charcoal records are a helpful proxy for understanding human impacts on island ecosystems and environments.

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Data availability statement

The data used in this study are archived in Data Dryad (DOI: 10.5061/dryad.f1c31).

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Tables

TABLE 1: Radiocarbon (^{14}C) dates of bulk sediment samples from Mare Tatos (Mauritius) used to establish the age vs. depth relationship (Fig. 1). Radiocarbon calibrations were done using ShCal13 and post bomb (Hogg *et al.* 2013, Hua *et al.* 2013, Reimer *et al.* 2013). pMC = percentage modern carbon, where modern is AD 1950. For further information on the calibration methods see online Supporting Information. * = first published de Boer et al. (2014).

Laboratory code	Depth in cm	pMC (1σ)	^{14}C years before present (1σ)	1σ range in calendar years AD/BC (probability)
D-AMS 017458	14.0	114.06 (±0.26)	modern	AD 1994-1992 (0.628) AD 1992-1992 (0.035) AD 1991-1991 (0.054) AD 1990-1990 (0.017) AD 1960-1959 (0.266)
D-AMS 017459	36.0	97.41 (±0.41)	211 (±34)	AD 1955-1950 (0.036) AD 1805-1728 (0.747) AD 1689-1664 (0.217)
D-AMS 017460	56.0	101.41 (±0.34)	modern	AD 1957-1957 (0.714) AD 1956-1956 (0.286)
GrA-51609*	66.5	-	260 (±30)	AD 1796-1780 (0.270) AD 1770-1763 (0.063) AD 1775-1745 (0.112) AD 1672-1643 (0.562)
GrA-51610*	180.5	-	2450 (±30)	401-510 BC (1.000)

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FIGURE 1: (A) Fire history of Mare Tatos wetland (Mauritius) since c. AD 1000 compared with key historical and ecological events. Historical data: dashed black line = percentage of modern human population (1,219,265 in 2014), and solid black line = percentage of natural vegetation. Open circle = first Dutch landing in Mauritius. Open square = French revolution. Grey horizontal bars = fire zones, defined by charcoal >20% of maximum of counts in size fraction 75-160 μm (landscape scale). Dark grey vertical dashed lines = presence/absence of fire threshold set at 5% of maximum charcoal values. Red icons and dotted horizontal lines = extinction events in the wild: Raven parrot (1680), Dodo (1690), giant tortoise (1700), and fruit bat (1795). Blue icons and dotted horizontal lines = introduction events: rats (14^{th} Century), cats (1598), locust (1720), and Java sparrow (1740). Information on extinction and introduction dates was obtained from: Cheke & Hume (2008) and Hume (2013). * = depth of radiocarbon date. (B) Mauritian land-cover based on historical documents. Open circile = Mare Tatos. Open square = Vieux Grand Port. Note: Historical data and maps are modified from Norder *et al.* (2017) and Floore & Jayasena (2010).