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Mauritius on fire: Tracking historical human impacts on biodiversity loss

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How to cite:

Gosling, William D.; de Kruif, Jona; Norder, Sietze J.; de Boer, Erik J.; Hooghiemstra, Henry; Rijdsijk, Kenneth F. and McMichael, Crystal N. H. (2017). Mauritius on fire: Tracking historical human impacts on biodiversity loss. *Biotropica*, 49(6) pp. 778–783.

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Version: Accepted Manuscript

Link(s) to article on publisher's website:
<http://dx.doi.org/doi:10.1111/btp.12490>

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1 For submission to: **Biotropica as an Insight**

2

3 Left running header: **Gosling *et al.***

4 Right running header: **Mauritius on fire**

5

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

7 **loss**

8

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25 Received _____ ; revision accepted _____.

26 **Abstract**

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

31

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

34

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

37

38 **Text**

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

53

54 The Dutch first settled Mauritius 40 years after their initial landings. During the
55 subsequent four centuries the island was occupied and abandoned by the Dutch (1638-
56 1710), French (1721-1810), and British (1810-1968), until it achieved independence
57 in 1968. Since the arrival of humans, Mauritian ecosystems have become degraded
58 through the overexploitation of species for food, the introduction of exotic species
59 (such as rats and cats), and the transformation of the landscape through clearance and
60 agriculture (Brouard 1963, Cheke & Hume 2008, Florens *et al.* 2012, Hume 2013,
61 Florens 2013, Norder *et al.* 2017).

62

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

77

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

87

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

102

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

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

116

117 Our data suggest that for c. 500 years prior to the arrival of the Dutch on
118 Mauritius, very little fire activity occurred at Mare Tatos, or within the surrounding
119 landscape (Fig. 1a). The rarity of pre-human fire is concordant with a c. 8000-year
120 reconstruction of micro-charcoal (c. 200 year between samples) from Mare Tatos (de
121 Boer *et al.* 2014). Fire became a major element of the landscape only after the Dutch
122 settled the island, which supports previous assertions that there were no significant
123 landings of people on Mauritius prior to the arrival of the Dutch (Cheke & Hume
124 2008, Floore & Jayasena 2010).

125

126 The first period of elevated fire activity on Mauritius (fire zone 1; c. 1630-1747)
127 is coincident with the first Dutch settlement on the island. Despite a population of just
128 a few hundred people, the charcoal signal evidences fire occurring at both regional
129 (<160 μm) and local (>160 μm) scales (Fig. 1a). The charcoal record detects fires
130 reflecting early clearance and cultivation in the bay area just c. 5 km north-west and
131 south-east of Mare Tatos (Floore & Jayasena 2010; Fig 1b, 1685 map). During fire
132 zone 1 forests were increasingly cut and burnt to provide space to grow crops, such as
133 sugar cane, rice, tobacco, indigo, vegetables and citrus trees (Brouard 1963, Grihault
134 2005). The peaks and troughs in the local charcoal signal within fire zone 1 could
135 reflect sporadic visits by people to Mare Tatos, possibly related to foraging
136 expeditions and/or selective logging for ebony trees.

137

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

153

154 Once established on Mauritius, the Dutch colonists faced a series of natural
155 (plagues, heavy storm damage) and political (lack of support from the mainland,
156 workers rebellion) difficulties, and abandoned the island in 1710 (Moree 1998). After
157 a decade of practically no human habitation the French settled Mauritius (Cheke &
158 Hume 2008). Fire remained a significant feature of the Mauritian landscape after the
159 governance transition (fire zone 1). The first major lull in fire activity on Mauritius
160 after European colonization occurred between c. 1747-1787, preceding the French
161 revolution (Fig. 1a), when land-based agricultural activities were of minor economic

162 importance compared to the provisioning of goods and services to passing ships
163 (Allen 1989, Addison & Hazareesingh 1999).

164

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

171

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

180

181 The major drop in fire activity c. 30 years after the onset of the major expansion
182 in sugar cane area in 1825 is coincident with the projected loss of c. 50% of the
183 natural vegetation on Mauritius (Fig. 1a). By c. 1850 most of the land suitable for
184 sugar cane agriculture on the northern part of Mauritius had been cleared, leaving no
185 natural vegetation left to burn (Fig. 1b, 1872 map). Management of the land for sugar
186 cane from 1833-1950 has left no significant charcoal record despite the practice of a

187 seasonal burning of the fields (Lalljee & Facknath 2008). The absence of a charcoal
188 (fire) signal likely reflects a shift from burning woody vegetation to burning crop
189 stubble (grass), because non-woody vegetation tends to produce less charcoal
190 (Whitlock & Larsen 2001).

191

192 It is not until the time of independence that fire activity again increased (c.
193 1950). Fire zone 3 reflects the transition to the current situation of c. 98 % loss of
194 natural vegetation on Mauritius. The elevated charcoal at Mare Tatos in recent times
195 likely reflects the burning of woody material brought into the area by humans,
196 possibly harvested elsewhere on the island, as by this point little local natural
197 vegetation remained (Fig. 1b). In the last decades, island wide degradation of
198 ecosystems is mainly linked to growing human populations, and an increase in
199 tourism and textile industries (Ramessur 2002).

200

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

210

211 During c. 500 years of human occupation the ecosystems of Mauritius were
212 degraded through forest fragmentation, fires, introduction of exotic species, and
213 overexploitation of natural resources (Cheke & Hume 2008, Rijdsdijk *et al.* 2011,
214 Florens *et al.* 2012, Rijdsdijk *et al.* 2015). Our research reveals that many extinction
215 events (including Raven parrot, Dodo, giant tortoise and fruit bat) over the last 500
216 years on Mauritius occurred during the periods of elevated human activity indicated
217 by frequent fire events recorded in the Mare Tatos sediments (Fig. 1a). All of these
218 species had suffered significant environmental pressures in the past, such as major
219 drought events, and survived (de Boer *et al.* 2015). Yet within c. 50 years of human
220 occupation, and the introduction of frequent fire events, the extinctions had begun
221 (Fig. 1a). The timings of the individual extinction events highlights the high
222 sensitivity of taxa to human activity, and the species-specific response to fire and
223 habitat loss. The coincidence of the greatest species loss with the first period of
224 elevated fire likely reflects the wide-ranging and high-level human interference on
225 Mauritius during this period. The reconstructed fire history of Mauritius suggests
226 that charcoal records are a helpful proxy for understanding human impacts on
227 island ecosystems and environments.
228
229

230 **Acknowledgements**

231 Sediments were collected as part of the Netherlands Science Foundation (NWO)
232 project (ALW 2300155042) granted to HH. SN received support from the Portuguese
233 National Funds, through FCT - Fundação para a Ciência e a Tecnologia, within the
234 project UID/BIA/00329/2013 and the research Fellowship PD/BD/114380/2016. We
235 thank the Mauritius Sugar Industry Research Institute for logistic support in the field.
236 We thank Claudia Baider (The Mauritius Herbarium, Réduit) for her continuous
237 support, Julian Hume and another anonymous referee for their detailed and insightful
238 comments which improved the quality of the manuscript.

239

240 **Data availability statement**

241 The data used in this study are archived in Data Dryad (DOI:
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243

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382

383 **Tables**

384 **TABLE 1:** Radiocarbon (^{14}C) dates of bulk sediment samples from Mare Tatos

385 (Mauritius) used to establish the age vs. depth relationship (Fig. 1). Radiocarbon
 386 calibrations were done using ShCal13 and post bomb (Hogg *et al.* 2013, Hua *et*
 387 *al.* 2013, Reimer *et al.* 2013). pMC = percentage modern carbon, where modern
 388 is AD 1950. For further information on the calibration methods see online
 389 Supporting Information. * = first published de Boer *et al.* (2014).

390

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)

391

392 **List of Figures**

393

394 **FIGURE 1:** (A) Fire history of Mare Tatos wetland (Mauritius) since c. AD 1000
395 compared with key historical and ecological events. Historical data: dashed
396 black line = percentage of modern human population (1,219,265 in 2014), and
397 solid black line = percentage of natural vegetation. Open circle = first Dutch
398 landing in Mauritius. Open square = French revolution. Grey horizontal bars =
399 fire zones, defined by charcoal >20% of maximum of counts in size fraction 75-
400 160 μm (landscape scale). Dark grey vertical dashed lines = presence/absence of
401 fire threshold set at 5% of maximum charcoal values. Red icons and dotted
402 horizontal lines = extinction events in the wild: Raven parrot (1680), Dodo
403 (1690), giant tortoise (1700), and fruit bat (1795). Blue icons and dotted
404 horizontal lines = introduction events: rats (14th Century), cats (1598), locust
405 (1720), and Java sparrow (1740). Information on extinction and introduction
406 dates was obtained from: Cheke & Hume (2008) and Hume (2013). * = depth of
407 radiocarbon date. (B) Mauritian land-cover based on historical documents. Open
408 circle = Mare Tatos. Open square = Vieux Grand Port. Note: Historical data
409 and maps are modified from Norder *et al.* (2017) and Floore & Jayasena (2010).
410