1 **Abstract**

2 Humans are increasingly viewed as active agents of environmental and land cover change in the

3 moist Neotropics. While the scale and extent of pre-Columbian anthropic impacts are actively

4 debated, the effects of post-Contact patterns of land use are rarely examined over the long term,

5 defined here as centennial timescales. This article examines a putative area of historical low human

6 impact located in the western Guiana Shield, the upper Cuao River, using an exploratory agent-

7 based modelling approach. Based on an extensive ethnographic literature on the Piaroa, who have

8 inhabited the region for at least four centuries, the model investigates the legacy effects of

9 ethnographic patterns of land use in the interval between European Contact and the present.

10 Model outcomes indicate that the potential range of anthropic changes to the environment of the

11 study area are significantly greater in scale than previously assumed. Interpretative discrepancies

12 between present vegetation conditions and the model are likely the product of sparse

13 palaeoecological and archaeological research in the upper Cuao. More broadly, the results imply

14 that small-scale agriculture and agroforestry can lead to extensive and persistent structural changes

15 to ecosystems in relatively short timescales. The experiment bolsters existing cautions against

16 assuming the "natural" baseline of Neotropic forests based on present appearance. As a form of

17 middle-range theory, the model demonstrates how computational approaches can promote closer

18 integrations between ecological, archaeological, and ethnohistorical data, as well as frame the

19 expectations of future research.

20

21 *Keywords: Agent-based modelling, Orinoco, Amazonia, simulation, Anthropocene, swidden agriculture*

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1. Introduction

The impact and legacy of indigenous land use practices continues to be a contentious area of research in the Neotropics (McMichael et al., 2012; Ter Steege et al., 2013; Stahl, 2015; Piperno et al., 2015; Watling et al., 2015; Watling et al., 2017; Piperno et al., 2017). Current debates in archaeology and historical ecology have moved on from dichotomous "cultural parkland" versus "pristine forest" scenarios (Denevan, 1992a; Heckenberger et al., 2003; Meggers, 2003), and focus now on defining the scale and extent of environmental modifications effected by the human inhabitants of Amazonia (Mayle and Iriarte, 2014; Clement et al., 2015). Critical readings of the ethnohistorical record frequently inform discussion on these topics, either to contrast with archaeological data, or to serve as a point of departure for useful comparisons between observed and archaeologically-inferred behaviours (Whitehead, 1998; Stahl, 2015). Crucially, the "wilderness" described in early European records of the Neotropics is now recognized to be, in many cases, an artefact of a post-Contact transition to an anthropogenic, yet largely human-free, environment that bears little resemblance to the pre-Columbian period (Denevan, 2016; cf. McMichael et al., 2012). Although colonization had disastrous consequences, which left measurable signals in the palaeoenvironmental and archaeological records (Faust et al., 2006; Bush et al., 2008), total demographic collapse and transition to historical patterns was not the only possible outcome (Ramenofsky, 1987; Thornton, 1987). The following examines the impact of historical indigenous land use in the interval between Contact and the present, in order to refine hypotheses and theoretical expectations for further field research

This study identifies the _long-term_ (centennial) consequences of historical indigenous land use as an area in need of scholarly attention, particularly where ethnohistorical, palaeoecological, or archaeological data are sparse. Short-term research on swidden agriculture (defined here as sub-generational) has for decades formed a programmatic part of Tropical forest research in ecology,

geography, and archaeology (Conklin, 1961; Harris, 1971; Cairns, 2015). Within the context of the European colonization of the Americas, suggested as one potential "tipping point" marking the onset of the Anthropocene (Erlandson and Braje, 2013), swidden agriculture emerged as the dominant agrarian subsistence strategy among post-Contact indigenous groups. This occurred under a particular set of internal and external societal pressures, as one strategy of many along a spectrum of possible responses by indigenous groups (Arroyo-Kalin, 2012; Balée, 2013: 185; Neves, 2013; Mayle and Iriarte, 2014). Swidden farming was also likely precocious among the first tropical forest cultivators, certainly making it a part of the complex legacy of human inhabitation in the Neotropics (Piperno and Pearsall, 1999; Oliver, 2001; Kirch, 2005; Roosevelt, 2013; Kawa, 2016). If the (circum-) Amazonian world is to be represented in the Anthropocene debate, it becomes necessary to be able to define the scale of historical indigenous environmental impacts in precise terms.

In parallel to historical ecology, yet largely isolated from it, is the growing adoption of simulation and model-based inferential frameworks in archaeological science (Kohler and van der Leeuw, 2007; Lake, 2014; cf. Johnson et al., 2005), including studies of coupled human-environmental systems and land cover/land use change (LUCC) in the past (Wilkinson et al., 2007; Barton et al., 2010; Barton, 2014). Driven by questions about human environmental impact, ecologists and geographers increasingly deploy computational approaches for exploring complex interactions between agents and ecosystem processes (Parker et al., 2003; Perry and Millington, 2008). Exploratory agent-based modelling (ABM), using known behaviours as a point of departure, are ideal for testing intuitions or hypothesis about a target system (Davies, 2016: 83). Computationally-minded archaeologists have already noted the synergy between experimental simulation on one hand (Godfrey-Smith, 2006; Potochnik, 2012) and middle-range theory in archaeology on the other (Premo, 2007; Davies, 2016). Simulation is perhaps best conceptualized as a "virtual laboratory" (Magliocca and Ellis, 2016) that serves to formalize assumptions about the operation

79 of a system of interest, quantify variability in model outcomes and, ultimately, test these against

80 knowledge claims. This is the approach adopted here.

81

82 The study aims to refine current understandings of the scale and temporality of impacts caused by

83 interfluvial slash-and-burn (swidden) agriculture in the moist Neotropics. Clearer insights into the

84 legacy and effects of post-Contact patterns of swidden agriculture is crucial to the agenda of

85 historical ecological research, and Anthropocene studies more broadly. The following synthesizes

86 a significant body of ethnographic work from the Orinoco, focusing on the Piaroa indigenous

87 group (see Zent, 1992; Overing and Kaplan, 2011), to investigate the variation in ecosystem

88 disturbances under swidden farming systems. This research was carried out in the context of a

89 larger project investigating indigenous occupations along the Middle Orinoco (Lozada Mendieta

90 et al., 2016). The model generalizes nearly half a century of anthropological and historical research

91 on Piaroa subsistence strategies, however, it does so usefully and explicitly (Epstein, 2008). I argue

92 that the lack of archaeological and environmental field research in the study area presents a gap in

93 knowledge which ethnographically-informed computational models may be particularly suited to

94 tackle.

95

96 **2.   Background to model: Piaroa interfluvial subsistence**

97

98 The Piaroa occupy the western edge of the Guiana Shield, an upland interfluvial zone in what is

99 today southern Venezuela. This area has historically received scant attention from archaeologists

100 and palaeoecologists, yet is rich in ethnographic data. The Piaroa are traditionally highly mobile

101 farmers whose subsistence is heavily reliant on manioc cultivated in short-lived plots of cleared

102 and burned forest, which is supplemented with fishing, hunting, and agroforestry. It is highly likely

103 that, due to disease, conflict, slaving, and new technologies following European contact, the

104 ethnographically-observed settlement pattern is contingent on recent historical processes (such as

105 the gradual spread of metal tools) rather than being the end state of an uninterrupted cultural

106 evolution (Denevan, 1992b; Huber and Zent, 1995: 48; Zent, 1998). Since the rural expansion of

107 the Venezuelan market economy and healthcare programmes in the 1980s, the Piaroa have

108 increasingly settled permanently along the main channel of the Orinoco and its navigable

109 tributaries to access to these services (Mansutti Rodriguez, 1988; Freire, 2007; Freire and Zent,

110 2007). Modes of subsistence recorded in the highland interfluvial zones, now considered their

111 "traditional" homeland, differ considerably from modern practices. In comparison to the Orinoco

112 floodplain, game is more dispersed, the rivers support fewer fish, and cropping cycles are

113 shortened while fallows are lengthened due to the shallow soils (Huber and Zent, 1995: 50). Still,

114 Zent (1995: 87), citing Gilij (1987), considers the Piaroa to have maintained stable settlement in

115 the uplands for 400 years at a minimum. As contact before the eighteenth century was sporadic

116 and archaeological data are non-existent in the interfluvial zone, this is an estimate for the duration

117 of occupation (Mansutti Rodriguez, 1988: 9; Zent, 1992: 48; Overing and Kaplan, 2011: 506).

118 Sáliva-speaking ancestors of the Piaroa were present in the upper-Middle Orinoco before this, but

119 the circumstances and duration of pre-Columbian settlement here is unknown at present.

120

121 Upland Piaroa settlements in the catchment of the Cuao River, a black water tributary of the

122 Orinoco (Figure 1), are typically organized around a single large house (Piaroa: *isodè*). This valley

123 forms the focus of the present study. Isodes are co-inhabited by an extended family or household

124 group of several extended families, consisting of 16-50 individuals (1-10 nuclear families), although

125 actual settlement population fluctuates somewhat due to high individual mobility. Camping trips,

126 visits, and temporary relocation can take place in a given year, with the home isode and its extended

127 family group acting as an anchor (Zent, 1998: 255). Overall population density is very low, with at

128 most 10 isodes per 100 km^2 "neighbourhood" (Monod, 1970; Overing and Kaplan, 2011). Isodes

129 can reportedly be occupied for as little as one year before relocation, or for 10 years or more (Zent,

130 1992; Heckler, 2004: 204).

131

[Insert Figure 1 here]

133

Although fishing, hunting, and wild resource gathering feature in the diversified Piaroa subsistence base, significant time and effort is invested in the swidden agricultural system, characterized by a short cropping phase (six years or less) followed by long fallows of 20 years or more (Zent, 1992: 184). Manioc (*Manihot esculenta*) and maize (*Zea mays*) together comprise nearly 80% of a harvest and supply the bulk of Piaroa caloric needs, with other wild and cultivated foods providing mainly supplementary nutrition (Zent, 1992; 1998; Overing and Kaplan, 2011: 514). Swidden plots, always cleared by slashing and burning climax forest, range in size from 0.25 to 6 ha, a figure that varies based on the number of individuals a plot will support. A nuclear family will generally self-sustain with a single swidden plot. A survey of 178 swidden plots in the upper Cuao corroborates this (Figure 1, bottom right), and shows a notable skew towards such plots (<2 ha in area, Perera, 1986; Zent, 1992: 190). When the productivity of a coeval group of ageing fields drops off due to vegetation succession and weed growth, members of an isode will relocate to the site of a former plot and establish a new settlement. Altering the forest cover exposes the thin tropical soils to depletion or erosion, in particular if secondary regrowth is cleared again after an insufficiently long fallow (<20 years) (Fölster, 1995: 70). The viability of subsequent cropping cycles and fallows will be severely curtailed if this occurs. Similarly, maintenance of swidden plots for longer than a few years risks limiting the regeneration potential of subsequent regrowth to bush fallow (Eden, 1974: 48). These pathways are typically avoided if at all possible, since fallowed plots and secondary forest both supply ecosystem services through improved hunting and gathering grounds (Harris, 1971; Zent, 1995). To summarize, Piaroa swidden farming in the upper Cuao is an interplay between meeting subsistence requirements, monitoring existing plots, and managing wild resources effectively, while avoiding intensive localised pressure on forest cover and overtaxing a limited pool of labour (Mansutti Rodriguez, 1988; Zent, 1992).

157

158 Modelling Piaroa subsistence practices and forest succession in the upper Cuao allows some

159 important aspects of post-Contact land cover and land use to be discussed. The implementation

160 of a small number of conservative and straightforward decision-making routines and parameters

161 is based on reasonable assumptions and derivations from the ethnographic literature. For instance,

162 the model uses a static or declining proxy for population, and swidden plots provide consistent

163 returns over their period of cultivation. The world initializes as a homogenous primary forest, in

164 which site selection is mostly unconstrained and guided only by economic logic insofar as it

165 impinges on farming. It slightly underestimates starting population density as roughly 1 isode per

166 118 km^2, below that estimated by Monod (1970), and does not consider isode migration or fission-

167 fusion dynamics. These serve to usefully constrain the number of factors considered in the

168 parameter space, and focus the discussion of the output. Rather than precisely mirroring every

169 aspect of Piaroa settlement patterns and subsistence behaviour, the model provides a reasonable

170 approximation, which allows for inferences to be made on long-term human-environmental

171 interaction.

172

173 **3. Model overview and design**

174

175 The above account of Piaroa socioecology is implemented computationally through a coupled

176 agent-based and cellular automata (CA) model based on spatial grid cells in NetLogo 6.0.1 (see

177 Wilensky, 1999; Moreno et al., 2007; Mena et al., 2011; Luus et al., 2013), to create an abstraction

178 of observed behaviour capable of investigating its long-term operation. The model parameters are

179 summarized in Table 1. For the study, individual isodes are treated as agents, with population per

180 isode generalized to the nuclear family level. At the start of a given run of the simulation, the

181 number of families is randomly assigned a value of 1 – 10, which determines the number of

182 swidden plots an isode will produce after each relocation to meet requirements. Isodes are

183   otherwise identical and do not interact, except for avoiding "claiming" active swidden plots owned

184   by another isode. As isode relocation is directly linked to the agricultural strategy (new house plots

185   are always established in old fields), a single parameter handles both swidden logistical range and

186   mobility magnitude (parameter 2). During a run, isodes monitor returns from surrounding grid

187   cells in range each time step and relocate to establish new swidden plots (*conucos*) when

188   requirements are not being met by existing fields. Grid cells targeted for swidden clearing always

189   consist of fallow secondary or primary forest. The model assumes that historically observed

190   clearance practices, employing efficient metal tools, are present at the start of a run. Stone axes,

191   for example in a pre-Contact scenario, would require different model assumption as to the time

192   and energy cost of creating clearings (Denevan 1992b). The choice of new house gardens when

193   relocating (parameter 3) can be varied to be a random cell out of the pre-existing swidden plots

194   owned by an isode, or optimized to always be the plot with the least regrowth. If, in any case, there

195   is an insufficient quantity of grid cells to meet requirements in logistical range, an isode may enter

196   a stressed state when relocating and lose a family (to death or outmigration). The likelihood of

197   stress events occurring is controlled by the magnitude of the deficit of available land.

198   [insert Table 1 here]
199

200   Vegetation succession and forest transition is handled as an integer by the cellular automata model,

201   mapped onto a simplified emic schema of forest regrowth stages (see Zent, 1992: 331; Zent, 1995:

202   91; Table 2), which functions on a per-grid cell basis. Grid cells regenerate from initial clearance

203   to initial secondary regrowth, with an equal likelihood of adding no growth (zero), little growth

204   (1), or significant growth (2) per time step. Each time step in the model approximates a season,

205   with two seasons per year. This introduces a degree of stochasticity as to when isode relocation

206   will take place, as plots may regenerate unevenly. As grid cells of secondary regrowth provide some

207   returns (a tenth of a swidden plot) in the form of mature tree stands and improved hunting, a

208 sufficient quantity of old gardens in logistical range could theoretically offset the gradual losses of

209 some fields becoming unproductive.

210

211 Forest succession (from bush to secondary forest, and from secondary to climax vegetation) are

212 modelled probabilistically (parameter 4). Every time step, grid cells with incipient or mature

213 secondary status (Table 2) count the number of surrounding primary forest cells. Every grid cell

214 of primary forest in the Moore neighbourhood (up to eight neighbouring cells) increases the

215 likelihood that stage succession will occur in increments of 0.025 per cell. The contribution of each

216 cell is varied as a model parameter (see Table 1), giving a range of values from 0.025 (a single

217 primary forest neighbour at the lowest parameter setting) to 1 (eight neighbours with primary

218 forest at the highest parameter setting). This implementation of forest succession approximates

219 the gradual colonization of fallowed plots by pioneer species and the maturation of economic tree

220 species planted by Piaroa at the start of its life cycle. It also reflects the long secondary regrowth

221 period (on average a century) typical of the nutrient-poor and fragile soils of the study area.

222

223 [insert Table 2 here]

224

225 The landscape employed in the simulations is a 609 by 426 cell digital terrain model of the upper

226 Cuao watershed (3568 km^2), resampled to half of its original resolution of 90 m to improve

227 processing time. Use of the terrain model (parameter 5) does not affect the behaviour of either

228 isodes or cells, but allows certain results of the parameter sweeps to be visualized more easily. The

229 initial state of the landscape assumes 100% primary forest cover. As noted above, there were

230 undoubtedly legacy effects of settlement in the landscape prior to the Piaroa uptake of swidden

231 agriculture. The present state of knowledge in the study area only allows these to be guessed at

232 and for present purposes, legacy effects have been left out. Each run of the model lasts for 800

233 time steps, equivalent to 400 years, or stops when all isodes have disbanded or expired. This

234 timeframe represents a hypothetical maximum for the presence of ethnographic Piaroa subsistence

235 behaviour in the study area: the seventeenth century to the present. Two sets of runs were carried

236 out separately due to prohibitively long processing times for large numbers of continuously

237 measured runs. The first set measured the end state of the landscape and isodes over 100

238 repetitions of each parameter combination (4500 runs), while the second set measured model

239 outputs diachronically over just 30 repetitions of each parameter combination (1350 runs).

240

241 **4.   Results**

242

243 This study modelled Piaroa land use through the interplay between mobility, population, and forest

244 regeneration potential to investigate legacy effects on the landscape of the upper Cuao. Figure 2a

245 summarizes the effects of isode mobility on the composition of primary forest in the study area.

246 This compares the number of grid cells that are never cultivated (old growth) against the total

247 amount of primary forest (old growth + reverted primary forest grid cells) at the end of 800 model

248 time steps, equivalent to four centuries. Grid cells of reverted primary forest are former swidden

249 plots that have succeeded back to climax vegetation after a century or more of fallow, making

250 them functionally indistinguishable from old growth primary forest to both Piaroa and non-Piaroa.

251 The pattern implies that as logistical radius (parameter 2) increases, the total amount of primary

252 forest remains stationary and very close to 98%, while unmodified primary forest sees a steady and

253 proportional decrease. Isodes in very low mobility regimes (logistical radius <=3) experience

254 frequent stress events due to the local depletion of arable grid cells, with coeval losses of

255 population. Loss reduces subsistence requirements, with the consequence of fewer cultivated grid

256 cells overall, leading to a lower ratio of reverted to old growth grid cells. Probability of regeneration

257 (parameter 3) has a negligible effect on the above outputs.

258

259   The total area roamed by a co-resident group of families is what Zent (1992) would term their

260   "neighbourhood". Forest succession in the upper Cuao is observably affected by the average

261   distance travelled by isodes from their origin, which is a function of logistical radius (Figure 2b

262   and c). Using this as a proxy for isode neighbourhood, changes in the proportion of grid cells with

263   scrubland ("incipient") regrowth and secondary forest both correlate with neighbourhood size.

264   Plotting the proportion of secondary regrowth against the proxy for neighbourhood, the variable

265   describes an S-shaped curve which fans out considerably as mobility increases, reaching a plateau

266   at approximately 20 grid cells from the origin (see Figure 2b). A plausible mechanism behind this

267   pattern is that high-mobility isodes are both: a) unlikely to suffer stress events and thus maintain

268   starting populations (due to a comparatively large logistical radius for establishing new plots), and

269   b) more likely to move further away from their starting position and disproportionately target old

270   growth primary forest over fallowed secondary forest for new swidden plots.

271

272   The highest proportion of incipient regrowth in the study area (up to 1% of all cells) is caused by

273   isodes that maintain a neighbourhood of 8-15 grid cells (Figure 2c). This can be suggested to be

274   the tipping point at which isodes can move a sufficient distance from their previous house garden

275   to avoid stress events (thus maintaining population levels) while creating new swidden plots close

276   enough to old plots to adversely affect their odds of regeneration to secondary forest. This results

277   in isodes creating large tracts of scrubland that have difficulty succeeding beyond this stage of

278   regrowth, due to a lack of nearby old growth forest from which to draw pioneer species. The

279   prevalence of incipient regrowth does not appear to impact on the relative proportion of secondary

280   forest, however.

281

282   [Insert Figure 2 here]

283

284 The average time grid cells spend as scrubland (a cumulative metric over the duration each run) is

285 also correlated with mobility magnitude. The peak in the latter between values of 2-4 (Figure 2d)

286 is likely due to the same mechanism identified above: short average distances between successive

287 house gardens. Due to the proximity of a given isode to its point of origin, and hence fallowed

288 plots, cleared grid cells are more likely to border grid cells from previous cropping cycle. In one

289 exceptional run, the _mean_ time grid cells spent as scrubland was 200 time steps, or a quarter of the

290 total length of the run. Runs with a logistical range of eight or higher display a sharp contraction

291 in the average time spent as scrubland. This is because an increase in the logistical radius of an

292 isode causes an exponential growth in the quantity of grid cells available for cultivation, reducing

293 the likelihood that fallowed swidden plots will affect the regeneration potential of new plots. This

294 is not true when mobility is lowered, which the results imply leads to outcomes with numerous

295 small yet persistent grid cells of scrubland.

296

297 Spatial visualization of some examples lends additional support to these trends, and provides some

298 useful contrasts between the influence of mobility magnitude on forest composition (Figure 3a).

299 Larger distances between new settlements results in more spatially diffuse tracts of anthropogenic

300 forest, although the absolute quantity of secondary forest is greater than in low mobility regimes

301 (see Figure 2b). Simultaneously, the amount of incipient regrowth is minimized by the distances

302 between swidden plots. Large swidden logistical radii leads to the appearance of tracts of modified

303 forest following long-term abandonment (>200 time steps), and the formation of diverse mosaics

304 of active swidden plots at different stages, secondary regrowth, and reverted primary forest (see

305 Figure 3a, inset). Smaller radii (low mobility) epitomizes the opposite, displaying spatially

306 circumscribed zones of secondary regrowth that frequently centre on groups of grid cells with

307 scrub vegetation (Figure 3b). These were observed to form through the mechanism hypothesized

308 from Figure 2c and Figure 2d, where isodes are unable to move far from old grounds, prolonging

309   the regeneration of incipient vegetation further. The temporality of anthropogenic land cover

310   change is therefore an important factor to consider.

311

312   [Insert Figure 3 here]

313

314   Examining model output diachronically permits three broad trends for incipient vegetation

315   formation to be defined (Figure 4). The first (A) indicates that low mobility causes an early and

316   rapid spike in the quantity of incipient forest plots, irrespective of regeneration potential. It was

317   hypothesized that this would cause frequent stress events among isodes, leading to a reduction in

318   total population and hence anthropogenic impact. This is not, however, borne out by the

319   experimental results; the legacy effects of early large-scale clearances persist until the end of runs.

320   Regeneration probability appears to exacerbate the magnitude of this outcome. The second trend

321   (B) displays a slower rise in incipient forest cover followed by plateaus or continued upward slopes

322   towards the end of runs. Finally, and in the majority, are the set of parameter combinations which

323   result in the creation of few, if any, persistent grid cells of incipient regrowth (C). The mean trend

324   is essentially flat. It is worth noting that, except for a single parameter combination (mobility = 6,

325   probability = 0.025), mobility is the key determinant of incipient vegetation trends, while

326   probability of regeneration only affects the magnitude of the trend.

327

328   [Insert Figure 4 here]

329

330   An additional experiment was conducted over a limited number of parameter combinations to

331   investigate changes in the returns of active grid cells over time (Figure 5). The model was allowed

332   to run for three times the number of time steps as in the previous simulations (2400) to detect any

333   long-term diachronic trends in its output that shorter runs might not capture. The most significant

334   qualitative differences in the shapes of these curves is again in low mobility regimes. Except for

where population starts to collapse within a few hundred time steps, the mean returns from active

fields (a) become stationary almost immediately. Conversely, the returns from secondary forest (b)

fluctuate significantly in the first 1000 time steps and only flatten out after approximately 1500

time steps, far beyond the duration investigated above. Kolmogorov-Smirnov tests indicate

significant differences between all four curves in both time series at $p < 0.001$, in addition to the

qualitative variability between parameter combinations. Extrapolating from Figure 5b, the ratio of

secondary forest to primary forest appears to reach a dynamic equilibrium, where on average only

approximately 2000 grid cells of secondary forest exist any point in time, or <2% of the modelling

domain. Secondary forest which has succeeded to climax vegetation (reverted forest) can be

predicted to continue to expand over time (see Figure 2a). Finally, while active plots and secondary

fields may appear comparable in terms of the sums of their returns, it is worth noting that swidden

plots in this model are by definition located within the logistical radius of isodes. Secondary forest,

on the other hand, can be widely distributed in the landscape of the upper Cuao (see Figure 3a)

and are not necessarily exploited synchronically.

[Insert Figure 5 here]

5.   Discussion

The aim of this experiment was to constrain the range of plausible scenarios for the scale of

impacts of Piaroa land use. Returning to this, assertions that the upper Cuao is a pristine

environment largely unaffected by significant land cover/land use changes over its history of

human inhabitation (Harris, 1971; Perera, 1986; Zent, 1992; Huber and Zent, 1995; Zent, 1995;

Freire, 2007) must be questioned in light of the modelling results. Instead, the modelling results

provide quantitative backing to the idea that groups of small-scale agriculturalists can cause

significant qualitative changes to an environment. In the context of Piaroa land use patterns, the

361 notion that shifting cultivation is necessarily a "high mobility, low impact" adaptation ought to be

362 modified. The results imply that the quantity of old growth forest affected by human action in the

363 interval since Contact may be up to four times greater than previously assumed, given the

364 parameter space explored in this case. Counterintuitively, high mobility _exacerbates_ this pattern

365 rather than diminishes it. The deleterious effects of shifting cultivation (deforestation, transition

366 to savannah, and attendant losses of resilience and biodiversity) emerge only under the most

367 extreme combinations of low mobility and environmental vulnerability. Under conditions where

368 forest succession is impacted over the long term, this manifests in a spatially-circumscribed

369 manner, centred on individual Piaroa isodes and their ranges (see Figure 3b).

370

371 Shifting swidden cultivation has been compared unfavourably with "the cumulative impact of

372 passive, small- to medium-scale and localized disturbance", meaning agroforestry (Stahl, 2015:

373 1600). While slash and burn farming is arguably an active form of landscape intervention, its impact

374 is demonstrably cumulative while almost by definition local in scale. In this respect, it is very similar

375 to the various types of terra firme agroforestry documented elsewhere in Amazonia that the above

376 quote refers to. Its persistent reputation as the _bête noire_ of Neotropical subsistence, viewed as

377 limiting to cultural development, wasteful, and ultimately unsustainable is only just being shed

378 (Arroyo-Kalin, 2012; papers in Cairns, 2015). The depth of indigenous knowledge on managing

379 swidden plot nutrient cycles, including biodiverse secondary forest, provides useful templates for

380 exploring this topic computationally (Harris, 1971; Denevan, 1992b). It is clear that the intensive

381 and sedentary pre-Columbian agricultural systems on the margins of rivers, such as those

382 responsible for the creation of anthropogenic dark earths in the central Amazon basin between

383 2500 and 500 BP, were far from being the only response to subsistence requirements. Indigenous

384 people developed and deployed a variety of different systems depending on the setting and

385 historical circumstances they faced (Arroyo-Kalin, 2010; Neves, 2013; McMichael et al., 2014),

386 each of which left imprints on the landscape. Against this backdrop, the Piaroa modelling

387 experiment must be tempered with palaeoenvironmental data implying low-impact and temporary

388 human occupation in the Amazonian interfluves since the initial colonization of the basin (see

389 McMichael et al., 2012; Levis et al., 2012; Watling et al., 2015; Stahl, 2015).

390

391 Although subordinate to manioc production, the Piaroa obtain a great variety of non-domesticated

392 resources from tracts of secondary forest (Zent, 1992; Overing and Kaplan, 2011). In the context

393 of this experiment, it is the emergence of diffuse yet extensive secondary forest tracts which

394 promote high logistical mobility as a comparatively sustainable pattern of land use. Conversely,

395 low mobility regime runs evidence how the odds of isode survival and the rate of forest succession

396 are adversely affected by the expansion of large scrubland tracts. The fact that the upper Cuao

397 today remains dominated by closed canopy forest suggests that pre-twentieth century land use

398 patterns tended towards the equivalent of "high mobility" runs. Due to the diffuse nature of Piaroa

399 swidden farming, extant tracts of secondary forest (and succeeding climax communities) may

400 become nearly undetectable to the untrained eye. Heckenberger et al., (2007: 197) note that satellite

401 imagery shows Amazonia to be largely flat and green, yet a look under the canopy reveals high

402 biocultural diversity. Johnson et al. (2005: 104) observe:

403

404   "[A]rchaeologists are not very good at estimating in their heads the effects over long periods of time

405 of slow processes […], particularly when those have to be weighed against a countervailing force such as forest

406 regrowth. It is important to address such processes in a quantitative framework to allow them to be

407 understood."

408

409 Taken together, the above observations by Heckenberger et al., (2007) and Johnson et al. (2005)

410 highlight a tension between "deep time" on one hand, and modern observational data on tropical

411 forests and their inhabitants on the other (e.g. Politis, 2007; Rival, 2016). While prior accounts of

412 tropical swidden farming societies (e.g. Conklin, 1961; Harris, 1971; Zent, 1992) are not incorrect

413   or guilty of errors of omission, the shallow time depth of ethnographic fieldwork relative to long-

414   term ecological processes may be a contributing factor to this apparent discrepancy. Historical

415   ecology aims to understand landscapes as historically contingent and emergent artefacts of human

416   activity, the products of centuries (if not millennia) of small-scale actions enacted across the entire

417   biosphere. Consequently, understanding how short-term mechanisms create enduring anthropic

418   patterns of landscape heterogeneity is high on the agenda (Balée 2006). Due to the nature of the

419   archaeological and palaeoenvironmental records, however, the focus tends to be on the *longue durée*

420   of human-environmental history through the aggregation of numerous unresolvable individual

421   actions (Isendahl, 2016).

422

423   Computational modelling grounded in ethnographic data to represent such actions has

424   demonstrated one way in which this gap may be bridged, using simple generative rules to explore

425   a series of "what if" scenarios (Lake, 2014; Cegielski and Rogers, 2016; Davies, 2016; Magliocca

426   and Ellis, 2016). Building on the premise that the Piaroa operated a system of swidden farming in

427   the upper Cuao for approximately four centuries lends further weight to the idea legacy effects in

428   tropical forests are more profound and pervasive than previously hypothesized. Going further, can

429   Piaroa secondary forest tracts be identified as post-Contact equivalents of pre-Columbian

430   "anthropic islands in a sea of forest" (Neves, 2013: 379)? If that is the case, the results suggest that

431   they are not only extensive but follow people around the landscape too. When viewed together

432   with the ephemerality and frequent movement of isodes in this environment, an archaeology of

433   the upper Cuao (like other interfluvial zones of the Neotropics) becomes a challenging prospect.

434   Extant ecological indicators of disturbance and yet-to-be-collected palaeoecological records, with

435   high-resolution radiometric age determinations, may be the only recourse to reconstructing the

436   pathways taken by the post-Contact Piaroa and their predecessors.

437

438   The present study area centres on only one of the secondary rivers occupied by Piaroa groups (and

439   other indigenous people) in the upper Orinoco valley (see Freire and Zent, 2007; Overing and

440   Kaplan, 2011), which was selected as the modelling domain specifically for its relative isolation

441   (see Zent, 1992). It is important to underline that it is not reasonable to expect these results to be

442   mirrored exactly in other parts of the Neotropics where swidden agriculture is practiced; the model

443   design was deliberately particularistic (cf. Barton 2013). Significant factors documented elsewhere,

444   such as the re-use of pre-Columbian landscape alterations (Heckenberger et al., 2007) do not play

445   a major role here. On a general level, however, the results do caution further against assuming a

446   that the baseline model for Neotropical forests should necessarily be a natural one, and here it is

447   relevant to note that a consensus on the definition of a "natural" Amazonian environment is itself

448   elusive (McKey et al., 2010: 7827; Clement et al., 2015; Watling et al., 2017). Placing this in a pan-

449   Amazonian context, understanding indigenous environmental impacts and their legacy may be a

450   question of identifying and translating between patterns observable at different spatio-temporal

451   scales (Arroyo-Kalin, 2010; Balée, 2013; Boivin et al., 2016; Levis et al. 2017). A key element of

452   this will be correctly identifying the longevity, magnitude, and cumulative effects of pre- versus

453   post-Contact indigenous impacts in different locations (McMichael et al. 2017).

454

455   This study of the post-Contact Piaroa shows that simulation may prove a valuable tool in achieving

456   this goal. Returning to the introduction, a fruitful path forward would be to develop comparative

457   frameworks for the degree and types of coupled human-environmental systems rather than re-

458   tread old debates contrasting spatially extensive, low impact patterns with those which are spatially

459   intensive and locally high impact. Without overstating the extendibility of this specific experiment

460   beyond the upper Orinoco, simulation and computational methods can help bridge ethnohistory,

461   archaeology, palaeoecology, and the subsistence regimes inferred or hypothesized to exist from

462   these sources of information on the past.

463

6.   Conclusions

The kinds of data that historical ecologists, anthropologists, and archaeologists are accustomed to handling demonstrably benefit from ever-closer integration. Advances in this area will be especially crucial to properly situating Amazonia in relation to human-induced changes in the biosphere observed globally (Kirch, 2005; Erlandson and Braje, 2013; Kawa, 2016). Computational modelling was adopted to characterize and develop a study of Piaroa ecodynamics, and proposed how discrepancies between the model and the reported environmental conditions of the upper Cuao may be resolved. By taking ethnographies at face value, the agent-based simulations suggest that the environments inhabited by these groups cannot be considered pristine by any metric, even in the relatively short time between European Contact to present. Furthermore, persistent concerns that conceptual models of subsistence in Amazonian risk overemphasising some parts of a system to the detriment our understanding of the whole (Whitehead, 1998: 38) is not a concern of formal, explicit models. A deliberate epistemic focus on "imagined concrete" properties (Godfrey-Smith, 2006: 738) of a real-world system, rather than precise isomorphism, enabled a robust consideration of the long-term effects of Piaroa swidden farming to be built from the ground up using aspects of known behaviours as a point of departure. The results suggest that the anthropic impacts of swidden farming in the modelling domain can manifest on very short timescales. This has implications for future investigations of the effect of millennia of agroforestry and intensification across the Neotropical world. As noted in the introduction, the ties between model-based science and middle-range theory (Premo, 2007; Davies, 2016) are worth exploiting for historical ecologists. Conceptual models, as semantic entities open to interpretation, will always have barriers between the intent of their original authors and their audiences. Although computational models are not a perfect replacement, they are also not vulnerable to this critique. With effort and informed theory-building anyone can extend, modify, or contest the model discussed here. Indeed, this is welcomed,

489 and may be instrumental to framing expectations for future archaeological research into tropical

490 forest cultures as agents of biodiversity and change.

491

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501

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