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Human occupation and ecosystem change on Upolu (Samoa) during the Holocene

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i) Title: ***Human occupation and ecosystem change on Upolu (Samoa) during the Holocene***

ii) Short title: ***Humans and ecosystem change on Upolu (Samoa)***

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vi) **Abstract:**

Aim: To track the peopling of the South Pacific and assess their impact on terrestrial and aquatic ecosystems

Location: Upolu, Samoa

Methods: A sedimentary record covering the last c. 10,500 years was recovered from the volcanic crater that contains Lake Lanoto'o near the centre of Upolu Island. Information on past ecological change was obtained from microscopic and macroscopic remains extracted from the sediments: charcoal (fire history), pollen/spores and plant remains (vegetation history), and lake status (algae/cyanobacteria). Information on the depositional environment and climate was obtained from geochemical and sedimentary analysis: loss-on-ignition (sediment composition), cryptotephras (volcanic eruptions), and precipitation regime (Ti/inc). The environmental history developed was compared with the archaeological record from the region.

Results: Charcoal material was found in the Lake Lanoto'o sediments at higher abundances and more frequently in samples from the period after the first archaeological evidence of people on Upolu (c. 2900-2700 years ago). No abrupt shift is recognised in the vegetation or aquatic ecosystem assemblages coincident with the arrival of people on the island.

Main conclusions: Macrocharcoal is demonstrated to be an effective proxy for detecting human occupation of Upolu around 2800 years ago. The immediate impact of these settlers on the vegetation seems to have been minimal, however, a subsequent opening up of the landscape is suggested through the gradual increase in ferns. The absence of any significant change in the aquatic community associated with, or after, the arrival of people on the islands suggests that humans rarely visited the lake. We suggest that on Upolu a simple model of decreasing human impact away from coastal areas is applicable.

Keywords: (x10) algae, aquatic, charcoal, cyanobacteria, fire, Pacific, pollen, Polynesia, terrestrial, vegetation.

vii) **Main text**

1. Introduction

Tracking the initial spread of humans around the globe allows an assessment of how humans have shaped ecosystems and landscapes. Identifying the first arrival of humans into a landscape, however, is often challenging because populations were likely small, transient, and often did not produce materials that are frequently preserved (Gosden, 1993; Graves & Addison 1995). Measures for assessing the arrival and impact of humans in ecosystems can be divided into two categories: (i) direct measures, which seek to obtain physical evidence of past human activity, and (ii) indirect measures, which infer past human activity from secondary observations. Aside from the discovery of sites or artefacts representing a past material culture, one of the most effective direct measures for tracking past human activity has been found to be the presence, and abundance, of ancient (fossil) charcoal found in soils or sediments (following Whitlock & Larsen, 2001). The use of charcoal to track past human activity has been shown to be particularly effective in tropical settings where natural fire is limited due to either a lack of ignition source or flammability, i.e. the appearance of fire is dependent on the arrival of humans (Argiriadis et al., 2018; Burney et al., 2004; Gosling et al., 2017; Huebert & Allen, 2016).

The South Pacific Islands (Oceania) are believed to contain some of last ecosystems on Earth to be colonised by humans (Fig. 1). Indirect evidence from linguistic and genomic analysis suggest that the dispersal of Austronesian speaking peoples into Oceania began c. 5000 calibrated years before present (cal BP) when it had reached as far as the Solomon Islands (Gray et al., 2009). Subsequently, people from the Bismarck Archipelago dispersed east c. 3000 years ago, and reached the easternmost islands of Polynesia within the last 1000 years (Gray et al., 2009; Matisoo-Smith, 2015). These dates are supported by direct archaeological evidence that suggests the homonid occupation of New Guinea began during the late Pleistocene (c. 50,000 years ago; Summerhayes et al., 2017), but that people did not reach western Polynesia until c. 2850 cal BP (Burley et al., 2012) or the easternmost islands, such as Rapa Nui (Easter Island), until c. 900-800 cal BP (Wilmshurst et al., 2011). The timing of human dispersal across the South Pacific in the Holocene has been linked to heightened periods of El Niño activity that elevated drought frequency and likely pushed peoples to migrate eastwards (Anderson et al., 2007).

The impact of the dispersal of human populations across the South Pacific, and the interplay between humans and climatic factors, in modifying ecosystems is the subject of ongoing debate (Kirch, 2017; Nunn, 2007; Spriggs 2014). It is likely that ecosystems on islands in the South Pacific were impacted by removal, and addition, of resources by the first peoples (Anderson, 1952; Flenley & King, 1984; Gosden, 1993; Prebble & Wilmhurst, 2009; Prebble et al., 2019). Many South Pacific island ecosystems are also known to be sensitive to changes in moisture availability (Mueller-Dombois & Fosberg, 1998), such as those resulting from changes related to the El Niño Southern Oscillation (ENSO) (Hassall, 2017; Zhang et al., 2014). Similarly, short lived abiotic events such as volcanic or tsunami events have been shown to have influenced the ecosystems on small islands through burial (Spriggs, 2014) or arrival of new species via rafting (García-Olivares et al., 2017). Unravelling the different drivers of ecosystem change has become important for understanding the dynamics of natural ecosystems and for discovering the specific impacts resulting from the arrival of humans. Here we present a new c. 10,500 year record of fire and ecosystem change from Upolu (Samoa) and assess the relative importance of humans, volcanic activity, and climate in shaping terrestrial and aquatic ecosystems.

2. Samoan archipelago

2.1 Geographical setting

The Samoan archipelago lies within the western Pacific Ocean and comprises 10 islands (13-14 ^{o}S, 170-173 ^{o}W). Just two islands, Savai'i and Upolu, make up 96% of the landmass (total 2934 km^2; Fig. 1). The Samoan islands were formed though volcanic activity during at least the last c. 1 million years as a consequence of the movement of the Pacific Plate (Hawkins, 1976; Kear, 1967; Kear & Wood, 1959). The geology of Samoa predominantly comprises basaltic cones that have been heavily eroded during the Pliocene and early Pleistocene, and are now buried by late Pleistocene lava flow deposits (Stearns, 1944). The last volcanic eruption in Samoa occurred on Savai'i in AD 1911 and on Upolu at some unknown time during the Holocene (Venzke, 2013). The majority of the modern Samoan flora is of Malaysian origin and can be divided into four groups broadly defined by altitude (Table 1).

The climate of the Samoan archipelago is controlled by the interplay between the South Pacific Convergence Zone (SPCZ), the Trade Winds, and the Inter-Tropical Convergence Zone (ITCZ). Mean monthly minimum (23-24 ^{o}C) and maximum (29-30 ^{o}C) temperature are relatively constant throughout the year, but precipitation can vary from >400 mm (January) to <150 mm (July). The climate of Upolu is classified as tropical, with a mean annual temperature of 26.6 °C and mean annual precipitation of c. 2800 mm (Lagomauitumua et al., 2011); with the south-east trade wind belt delivering slightly more rain to the southern region. No distinct dry season exists, but during November and April it is generally warmer and wetter with a greater frequency of tropical storms and hurricanes (Mueller-Dombois & Fosberg, 1998). Strong year-to-year climatic variation has been observed to occur related to the movement of the SPCZ during different ENSO phases, i.e. the La Niña phase delivers more wet season rainfall, while the El Niño phase leads to relatively drier conditions (Lagomauitumua et al., 2011). Sedimentary archives of past climate on Samoa have been reconstructed over the Holocene and show abrupt changes in precipitation proxies interpreted to indicate regional changes in the position and intensity of the SPCZ (Hassall, 2017).

2.1 Human history

The earliest evidence for human occupation of Samoa comes from radiocarbon dates associated with artefacts found at the Ferry Berth archaeological site near the coastal town of Mulifauna (Upolu) (Leach & Green, 1989; Petchy, 2001; Petchy & Kirch, 2019; Reith & Hunt 2008). The pottery and adze's found at the Malifauna site are characteristic of the Lapita culture (c. 2900-2700 cal BP) and are made of local material (Leach & Green, 1989). The wide-spread scatter of archaeological finds (Davidson, 1969), and identification of ancient building structures through remote sensing techniques (Jackmond et al., 2018), across the island indicates occupation of large areas during some period, or periods, prior to European contact in AD 1840 (110 cal BP). Current archaeological evidence from settlement sites on Upolu, however, suggest that human populations may not have moved to inland locations until late in the islands occupation: 1500-1000 cal BP (Morrison et al., 2015), c. 595 cal BP (AD 1355) at Cog Oven and c. 315 cal BP (c. AD 1635) at Mount Olo (Jennings et al., 1982).

Patterns of social organisation are not thought to have greatly altered through the period of human occupation of Samoa (Wallin & Martinsson-Wallin, 2007), however, a four step sequence of settlement patterns has been suggested (Green, 2002; Morrison et al 2015): (i) c. 2900-2700 year ago linked to Lapita decorated ceramics, (ii) c. 2700-2000/1500 years ago linked to Polynesian plainware ceramics, (iii) c. 1500-1000 years ago "Samoan Dark Ages" when settlement pattern evidence is limited at the coast but is present inland, and (iv) c. 1000-200 years ago. The reasons behind the pre-historic changes in settlement patterns on Upolu remain ambiguous and they have not, to date, been directly associated with external factors; however, the subsequent arrival of Europeans on the islands is seen as a major driver of change (Wallin & Martinsson-Wallin, 2007).

3. Materials and methods

3.1 Study site: Lake Lanoto'o (Upolu island)

Lake Lanoto'o (171^o 50' W, 13^o 54' S) is a 0.11 km^2 volcanic crater lake at the centre of Upolu island c. 760 m above sea level (asl) with a catchment area of 0.23 km^2. The Salani volcanic deposits that define the region are thought to have formed between c. 310,000 and 64,000 years ago (Kear & Wood, 1959). Today the lake is c. 400 m diameter with a maximum depth of 17.5 m (Fig. 1), in the surface layers lake water is pH 7, with a a temperature of c. 27 °C, Oxygen saturation of 105 %, and a conductivity of 15 µs/cm (measured in September 2014). At c. 10 m depth a thermocline results in a relatively abrupt change to cooler (23°C) anoxic conditions (dissolved Oxygen 10%), pH 4, and increased conductivity 21 µs/cm (Hassall, 2017). Lake Lanoto'o is boarded by steep slopes that reach up to 790 and 770 m asl to the east and west respectively. The soils that surround the lake today contain highly weathered red lateritic clay with low silica but high TiO_2 content (Wright, 1963) and are vegetated with dense montane forest (Olsen et al., 2001; Whistler, 1992).

3.2 Sediment

3.2.1 Core recovery

A sequence of overlapping cores was obtained from the deepest region of Lake Lanoto'o in September 2014 (Fig. 1). A UWITEC gravity-type corer was used to recover the upper 60cm. A cam-modified piston corer was used to retrieve overlapping sediment cores to a depth of 302 cm below the mud-water interface (Colinvaux et al., 1999). All cores were stored intact in airtight tubes and kept in cold storage (+4 °C) at the University of Southampton (UK). Sub-samples were subsequently extracted from the cores for radiocarbon dating and palaeoecological analysis.

3.2.2 Core analysis

The cores were correlated on the basis of sedimentary characteristics determined by Loss-on-Ignition (LOI), magnetic susceptibility, and Itrax core scanning data (Fig. 2). True core depths (cm below mud-water interface) were then re-calculated to form a single composite depth model that was, in turn, used for age vs. depth modelling.

Loss-on-ignition analysis was applied to contiguous 1 cm^3 subsamples (following Lamb, 2004). Whole cores were measured for volume-specific low frequency magnetic susceptibility using a Bartington Instruments MS2K sensor at contiguous 1 cm intervals (following Dearing, 1994). Geochemical analysis was undertaken using an Itrax core scanner (Cox Analytical Systems, Gothenburg, Sweden) (following Croudace et al., 2006) and %C and %N (used to calculate C/N) using an elemental analyser. A Molybdenum tube (30 kV, 30 mA) was used to scan each core at 500 μm resolution and at 200 μm for the surface Gravity core. The analytical dwell time was set at 30 seconds.

3.3 Age vs. depth model

Radionuclide dating was used to generate and age model for the Lake Lanoto'o sediments. For the surface Gravity core the activity of ^{137}Cs and ^{210}Pb was measured using Canberra well-type HPGe gamma-ray spectrometers (Canberra UK Ltd., Didcot, UK – now Mirion Technologies). The gamma ray spectra were acquired for 100,000 s for each contiguous 0.5 cm samples and processed using Fitzpeaks gamma deconvolving software (JF Computing, Stanford-in-the-Vale, UK). All measurements were undertaken at the Geosciences Advisory Unit (GAU)-Radioanalytical Laboratories based at the National Oceanography Centre, Southampton (Croudace et al., 2012).

The CRS model was applied to the resulting ^{210}Pb profiles to account for variations in accumulation rate and has been used in other sites in the Pacific (following Zhang et al., 2014). Our CRS model obtained r^2 values of 0.91, $p<0.0001$. We tested the model using the independent ^{137}Cs estimates for bomb fallout identified at 9 cm (AD 1954±1) when appreciable fallout levels of ^{137}Cs in the atmosphere first occurred, and the peak at 7 cm which was ascribed to the AD 1964±1 fallout peak (Croudace et al., 2012; Terry et al., 2006). The ^{210}Pb CRS model for Lake Lanoto'o produced comparative dates of AD 1953±1 at 9 cm and AD 1966±1 at 7.5 cm. Average accumulation rates using this model for the upper sediments in Lake Lanoto'o were 9.92 years per cm.

Radiocarbon (^{14}C) measurements were obtained from 18 bulk sediment samples using the acid-alkali-acid pre-treatment method at SUERC (Table 2). All dates were reported in conventional ^{14}C years before AD 1950, with analytical confidence expressed at the $\pm 1\sigma$ interval. Radiocarbon dates were calibrated to calendar ages using the SHCal13 curve for southern hemisphere (Hogg et al., 2013).

All dates were used to create an age vs. depth model for Lake Lanoto'o in BACON 2.2 Bayesian modelling software (Blaauw & Christen, 2011) (Fig. 2). Whilst the majority of the dates are stratigraphically consistent throughout the sequence, BACON highlights two samples (LAN14-2-2 11-12cm and LAN14-1-3 17-18cm) that are outliers, the former being older than expected and the latter being younger than expected.

3.4 Palaeoecological analysis

Two different sets of sub-samples were processed from the Lake Lanoto'o sediment core to extract different types of palaeoecological information: (i) microscopic remains, to reconstruct regional fire history (microcharcoal), vegetation history (pollen), and lake status (algae and cyanobacteria), and volcanic eruptions (cryptotephra), and (ii) macroscopic remains, to reconstruct local fire history (macrocharcoal), and local vegetation (plant remains).

3.4.1 Microscopic remains: Microcharcoal, pollen, spores, algae, cyanobacteria and cryptotephra

One cubic centimetre sub-samples were prepared for microscopic analysis using standard protocols (Moore et al., 1991), including density separation, acetolysis and sieving at 180 µm. A *Lycopodium* tablet (University of Lund, batch #483216, containing 18,583 grains ±4.1 %) was added to each sample to allow the calculation of concentrations (following Stockmarr, 1971). Examination of material was done using a Leica DMBL microscope at 400x and 1000x magnification. Microcharcoal, pollen and spores were identified and counted in parallel (32 samples). Algae and cyanobacteria were identified and counted in parallel (58 samples). Microcharcoal counts were obtained following guidelines on identification described in Whitlock & Larsen (2001). A threshold of ≥ 5 % of the maximum value was used as an indication of microcharcoal input over potential background (following Kelly et al., 2011). Pollen and spore identifications were achieved through comparison with the reference collections at the University of Amsterdam and Utrecht University, and published atlases (APSA Members, 2007; Roubik & Moreno, 1991). Pollen and spore sums of >300 grains were achieved for each sample, excluding Cyperaceae. Algae and cyanobacteria were identified through comparison with reference material at the University of Amsterdam and published atlases (Canter-Lund & Lund, 1995; Medeanic, 2006; Poulíčková et al., 2007; van Geel, 1976; van Geel, 1978). Algae and cyanobacteria were counted until sums of >300 had been achieved.

Cryptotephra layers were identified following subsampling of contiguous 5 cm-long sections throughout the entire core sequence. Cryptotephras were extracted by sieving to recover the 125-25 µm fraction, and density separation using sodium polytungstate; cleaning float of 1.95 g cm^{-3}, extraction float of 2.5 g cm^{-3} (following Blockley et al., 2005). The supernatant of the extraction float was mounted on glass slides in Canada Balsam and scanned for presence of glass shards under an optical microscope fitted with cross-polarising filters. The numbers of shards were then counted and concentrations per gram of sample (dry weight) calculated. Where tephra shards were identified the sample resolution was refined to 1 cm.

3.4.2 Macroscopic remains: Macrocharcoal, plant remains, and sediment composition

Eighty-six 1 cm^3 sub-samples were prepared for through bleaching with 3 % H_2O_2 on a hotplate at 150 ^{o}C for 15 minutes, and sieving at 160 µm. Identification of macrocharcoal, plant remains and sedimentary material was done simultaneously using a Leica MZ16 stereo microscope at 0.71-11.5x magnification. Macrocharcoal was identified based upon colour (black), shape (angularity) and breakage pattern when pressure was applied (splintering), following Whitlock & Larsen (2001). Macrocharcoal particles were counted and digitally photographed using a Fuji X-M1 camera. The images of macrocharcoal particles were analysed in ImageJ to calculate area (Rasband, 2008). A threshold of ≥ 5 % of the maximum value was used as an indication of macrocharcoal input over potential background, following Kelly et al. (2011). Plant remains identifications were achieved through reference to collections at the University of Amsterdam.

3.4.3 Statistical analysis

Detrended Corresponance Analysis (DCA) was used to characterise the major trends in the pollen and spore, and algae and cyanobacteria datasets. Percentage abundance data for all taxa were used in both cases. The DCA analysis was performed in R v. 3.5.1 (R Core Team, 2018) using the package Vegan v. 2.5-2 (Oksanen et al., 2017).

4. Results

4.1 Sediment characteristics

The Lake Lanoto'o sediment core was found to comprise two distinct sediment types: (i) orange coloured (Munsell 7.5YR 5/6) sediments with high titanium (Ti/inc), high magnetic susceptibility (K), high C/N ratio and low organic carbon, and (ii) dark brown coloured (Munsell 7.5YR 2.5/5) sediments with low titanium (Ti/inc), low magnetic susceptibility (K), low C/N ratio and high organic carbon (Fig. 3). At one point in the core (181-180 cm, c. 6837 cal BP) rounded silicate sand (> 160 µm) was found within the sediment in an obliquely slanting layer that extended over 7.3cm.

4.2 Microscopic remains

4.2.1 Microcharcoal

Prior to the first archaeological evidence of humans on Upolu (c. 2800 cal BP) microcharcoal was found in six of the 19 samples examined (32 %), while in the post-occupation period 13 out of 14 samples were found to contain microcharcoal (93 %). Furthermore, the older samples contained low abundances (mean 1199 particles/cm^3) of microcharcoal when compared with the more recent period (mean 7848 particles/cm^3) (Fig. 3). One sample in the pre-archaeology period contains an abundance of microcharcoal equivalent to the post-archaeology period; c. 11,400 particles/cm^3 at c. 4200 cal BP.

4.2.2 Pollen and spores

Throughout most of the last c. 10,500 years Moraceae/Urticaeae (mean 14 %), monolete spores (13 %), Myrtaceae (12 %), and *Weinmannia* (9 %) have been major components of the pollen/spore assemblage at Lake Lanoto'o (Fig. 4). Large variations in abundance, however, are observed in a number of taxa before, and after, the first archaeological evidence of humans on Upolu, notably: Myrtaceae (range 1-33 %), Moraceae/Urticaceae (5-32 %), *Wienmannia* (2-27 %) and *Pandanus* (0-24 %). Following the archaeological evidence of humans on Upolu it is notable that Myrtaceae does not reach above 5 %, while Cyatheaceae gradually increases from around 4 % at c. 3000 cal BP up to over 10 % by c. 1200 cal BP. There is no observed change in the concentration of pollen/spores within the sediment coincident with the first archaeological evidence of humans on Upolu, but changes in abundance of taxa indicate the largest sustained change in the pollen assemblage in the last c. 10,500 years (DCA1 scores, Fig. 4).

4.2.3 Algae and cyanobacteria

Algae and cyanobacteria were found in high concentrations (mean 1,500,000 per cm^3) throughout the Lake Lanoto'o sediment core, except for the period between c. 6500-5300 cal BP when concentrations drop dramatically (< 250,000 per cm^3) (Fig. 5). During periods of high concentration the algae and cyanobacteria assemblage is comprised predominantly of *Botryococcus* (11-50 %). During the period of low concentration the assemblage mainly comprises four types of algae/cyanobacteria that have not been taxonomically assigned: Type 128A (up to 25 %), Type 128B (up to 54 %), and Type A (up to 21 %) (van Geel, 1976; van Geel, 1978). There is no change observed in the algae and cyanobacteria community coincident with the first archaeological evidence of humans on Upolu.

4.2.4 Tephra

Cryptotephra particles were found in three samples from the Lake Lanoto'o sediment core at: 292-287 cm (c. 10,063-9775 cal BP), 109-104cm (3829-3576 cal BP, 1879-1626 BC), and 14-13 cm (81-62 cal BP, AD 1869-1888) (Fig. 2). Within these samples between 70 and 10,000 tephra particles per gram were found.

4.3 Macroscopic remains

3.3.1 Macrocharcoal

Macrocharcoal is absent from the Lake Lanoto'o sediments prior to the earliest archaeological record of humans on the island around c. 2800 years ago (Fig. 3). Within the last c. 2800 years marcocharcoal fragments were found in nine of the 32 (28 %) samples analysed. Macrocharcoal particle counts within the last c. 2800 years ranged from 0 to 9, with the maximum area of charcoal recorded occurring at c. 1200 cal BP (0.86 mm^2); all but one of the occurrences of macrocharcoal exceeded 5 % of the maximum area value (0.04 mm^2).

4.3.2 Plant remains

Three types of macroscopic plant remains were identified within the sediments from Lake Lanoto'o. One of these was identified as fern sporangia, while the other two were identified as seeds from an unknown plant (Appendix 1). The fern sporangia and Type-2 plant remain from Lake Lanoto'o were present intermittently throughout the entire record. The Type-1 plant remains first appears in the Lake Lanoto'o record c. 4200 cal BP.

5. Discussion

5.1 Fire and the human occupation of Upolu

Macro- and microcharcoal are commonly interpreted as evidence of burning in the local and regional environment (Clark & Royall, 1996). The definition of what is considered 'local' versus 'regional' is depended on the site-specific setting and conditions, important factors include topography and prevailing wind direction (Whitlock & Larsen, 2001). In the case of Lake Lanoto'o the macrocharcoal signal could be derived from two sources: (i) burning within the small catchment (0.23 km^2) immediately around the lake, and (ii) burning on the coast c. 9 km to the south, i.e. fires > 0.02 km^2 can generate convective columns >1000 m (Palmer & Northcutt, 1975) that are capable of transporting macrocharcoal c. 10 km (Clark, 1988). It seems, however, unlikely that macrocharcoal material could reach Lake Lanoto'o from beyond the shores of Upolu as the main neighbouring island is c. 50 km north-west. Microcharcoal, however, is known to travel 10s kms from its source (Clark, 1988), so could have reached Lake Lanoto'o from fires anywhere on Upolu or on a nearby island.

The first appearance of macrocharcoal in the Lake Lanoto'o sediments occurs at c. 2700 cal BP, and is (within analytical uncertainty) within the dates from the earliest archaeological evidence for human occupation on Upolu (Fig. 3). The close agreement between the macrocharcoal and the archaeological evidence suggests that humans were necessary to provide a source of ignition and/or sustain fire on Samoa, and mirrors similar patterns seen on Vanuatu, New Caledonia, and Fiji (Hope et al., 2009). The abundance of macrocharcoal found within the Upolu sediments is low (below 10 particles per cm^3) when compared with abundances found in sediments known to be associated with large-scale landscape clearance (above >200 particles per cm^3) on Mauritius (Gosling et al., 2017). The relatively low abundance of macrocharcoal on Upolu suggests that either fire activity within the lake catchment was very limited, or that larger scale fires elsewhere on the island contributed material via long-distance transport. Both interpretations fit with the idea that initial colonisers focused on coastal areas (Cochrane et al., 2016).

Archaeological evidence indicates that settlements had appeared throughout the Samoan archipelago by c. 2100 cal BP (Reith & Hunt, 2008). However, during the Samoan Dark Ages (c. 1500-1000 cal BP) there is a comparative absence of archaeological evidence on Upolu at the coast. Intriguingly, the largest peak in macrocharcoal (by area) in the Lake Lanoto'o sediments occurs during the Samoan Dark Age period (c. 1200 cal BP) and macrocharcoal was found in 40 % of the samples analysed during this time window (Fig. 3). The continued presence of charcoal within the Lake Lanoto'o sediments confirms that humans continued to be present on the island during the Samoan Dark Ages, and corresponds with preliminary evidence of increased inland settlement at this time (Morrison et al., 2015). The idea of more widespread past human populations on Upolu is supported by recent analysis of LiDAR data which shows a wider distribution of human made structures across the island than was previously thought (Jackmond et al., 2018).

The microcharcoal record follows the major trend of the macrocharcoal with persistent occurrence only after the first archaeology, i.e. microcharcoal is above background levels in all samples after 2900-2700 cal BP (Fig. 3). However, the microcharcoal record suggests that fire was present on Upolu, and/or nearby islands, prior to the start of the archaeological record (background levels are exceeded in six of the 20 pre-archaeology samples analysed). The large early peak in microcharcoal at c. 4200 cal BP is not mirrored in the macrocharcoal record, but is coincident with a shift in the pollen assemblage and the first appearance of an unknown seed (Fig. 4). The change in the pollen assemblage is driven by a replacement of Myrtaceae with Moraceae/Urticaceae, both common components of the montane and lowland forests, which perhaps indicates that fire was impacting ecosystems at lower elevations. The Type 1 plant remains (probably a grass seed M. Prebble pers. comm.) could indicate a new arrival on the Upolu, or be indicative of a plant becoming more successful under the changed conditions. The early peak in microcharcoal, and associated vegetation changes, could be tentatively interpreted as indicative of a short-lived human visit to Upolu (or a nearby island) or due to climatic changes around c. 4200 cal BP; however, both explanations remain open to discussion:

- If a short-lived human visit is invoked then this would place people on Upolu c. 1200 years before the earliest archaeological evidence on the island (Petchy & Kirch, 2019) and prior to the current earliest estimates of the colonisation of Remote Oceania (c. 3000 cal BP, Sheppard et al., 2015; 3500-2800 cal BP Anderson, 2009). The closest dated archaeological evidence in the South Pacific prior to c. 4200 cal BP comes from the Solomon Islands, >3000 km west, which has been inhabited for around 5000 years (Gray et al., 2009). Consequently, a small population would have had to make a long leap to have arrived on Upolu by c. 4200 cal BP to be responsible for the charcoal particles.
- If a climate explanation is invoked there is an elevated global aridity event around c. 4200 cal BP could be responsible (de Menocal, 2001); however, independent indicators of precipitation from the Lake Lanoto'o' core suggest this was the wettest period since sediment accumulation began (Hassall, 2017). To make Upolu wet whilst increasing aridity (and burning) elsewhere in the South Pacific could be possible given a southward shift in the ITCZ and SPCZ (Emile-Guey et

al., 2016; Sachs et al., 2018) which would have resulted in wetter conditions on Upolu and allowed microcharcoal transport from arid areas.

Interestingly there are distinct increases in fire (charcoal abundance) at two sites on Fiji, Volivoli and Navatu, at c. 5200 and c. 4000 cal BP respectively which are attributed to lightening strikes during drier El Niño conditions (Hope et al., 2009). This and the absence of archaeological or sedimentary evidence to support early human populations on intervening islands currently favours the climatic hypothesis; however, alternatively this peak may just represent a chance fire event caused by volcanic activity or a lightening strike somewhere in the region.

5.2 The impact of humans on the ecosystems of Upolu

Lake Lanoto'o has a diameter of c. 400 m suggesting that around half of the pollen captured within the sediments likely came from further than 100 m from the lake (termed 'regional' following Jacobson & Bradshaw, 1981). The prevailing winds from the south-east likely transport pollen upslope and consequently bias, and expand, the range of the signal to vegetation found on the southern side of the island. The pollen data indicates that Moraceae/Urticaeae, Myrtaceae, *Weinmannia* and ferns were the major components of the terrestrial vegetation for most the last c. 10,500 years (Fig. 4). Significant changes are observed in all of these taxa before, and after, the first archaeological evidence of humans on Upolu indicating a naturally dynamic vegetation mosaic.

The certain arrival of humans on Upolu c. 2900-2700 cal BP, as indicated by the archaeological and the macrocharcoal record (Fig. 3), is coincident with changes in the relative abundance of terrestrial taxa commonly found in montane and lowland forests and a climatic drying (Hassall, 2017). Following the initial replacement of Myrtaceae with Moraceae/Urticaceae the subsequent gradual increase in Cyatheaceae pollen is the most notable change. The gradual increase in the abundance of Cyatheaceae interestingly mirrors the pattern observed in the Galapagos (Restrepo et al., 2012) and Mo'orea (Stevenson et al., 2017), and the increase in fern species more generally found on Rimitara (Austral Islands) (Prebble & Wilmshurst, 2009) and on Atiu, Mangaia and Rarotonga in the Cook Islands (Fujiki et al., 2014; Kirch & Ellison, 1994; Parkes, 1997). The Cyatheaceae and fern signals on these islands have been interpreted as indicative of an opening up of the landscape by humans and a similar explanation seems likely on Upolu.

The gradual nature of the suggested landscape opening on Upolu indicates an incremental human impact that mirrors trajectories of change observed on Fiji (Roos et al., 2016), but is in contrast to abrupt impacts recorded in Rapa Nui (Flenley & King, 1984; Rull 2016). It is likely that, in all situations, the ratio between the human population size and the amount of available land and coastal areas plays an important role on the degree of impact. Smaller islands are therefore likely to be more vulnerable to rapid landscape transformation by the arrival of humans. The incremental nature of terrestrial ecosystem change on Upolu suggests that the initial human populations may have been quite small relative to the island size, mirroring inferences drawn from data related to the size of the language phylogenies (Gray et al., 2009), and the low number of archaeological sites found during this early period (Cochrane et al., 2016; Leach & Green, 1989). Initial human impact on Hawaiian Islands exhibits a similar spatial pattern with rapid changes seen to occur shortly after occupation in coastal areas (Athens et al., 1992) while remote inland areas remain relatively unaffected (Selling, 1948).

The major component of the algal community within Lake Lanoto’o for most of the last c. 10,500 years is *Botryococcus* (Fig. 5). There is no significant change in the algal or cyanobacteria community composition or concentration at, or following the first archaeological evidence of humans on Upolu (c. 2800 cal BP). The absence of any significant change in the algae/cyanobateria of Lake Lanoto’o during the period of human occupation suggests that human activity at, or near, the lake did not impact water quality or aquatic ecosystems. The absence of any discernible impact on the aquatic community is commensurate with the interpretation from the charcoal record of a low level, or absence, of humans at Lake Lanoto’o.

Our data support the view that the impact of the arrival of humans on islands is strongly controlled by the local scale and conditions of each island (Kennett et al., 2006; Prebble, 2006). On larger islands, extensive coastal landscapes buffer rapid modification by, initially small, colonizing populations; however, as populations grow the intensity and extent of landscape change inevitably increases. Remote locations on islands, such as Lake Lanoto’o, consequently appear to be buffered by the geography against major human induced ecosystem change and are thus important sites of native biodiversity reflected in the protected status of this site.

5.3 Non-human drivers of ecosystem change on Upolu

Humans seem to have played no role in modifying ecosystems on Upolu prior to c. 2800 cal BP. However, since significant changes are recorded in the palaeoecological record, it is therefore necessary to look for alternative explanations (Fig. 6). Independent sedimentological evidence from Lake Lanoto'o provides some insights into the likely drivers of these changes (Fig. 3).

Three volcanic events have been identified through cryptotephras within the Lake Lanoto'o sediments, but no discernable response is found in either the terrestrial or aquatic communities (Fig. 4 and 5). Similar sized lakes in tropical settings have been shown to suffer community turnover in response to the deposition of volcanic tephra (Matthews-Bird et al., 2017). The absence of a response on Upolu likely reflects a comparatively low input of volcanic material. The highest concentration of cryptotephra was found between AD 1869 and 1888 (81-62 cal BP) and could represent a precursor to the documented eruption on Savai'i in AD 1911 (Venzke, 2013).

The presence of siliceous sand in the Lake Lanoto'o sediments at c. 6700 cal BP is soon after a rapid decline in the abundance of algal and cyanobacteria found within the Lake Lanoto'o sediments (Fig. 5). This section of the core is also subject to the greatest uncertainty within the age vs. depth model (Fig. 2). The presence of sand and reversed radiocarbon dates may indicate that a significant perturbation of the sediment occurred, such as a landslide, which altered the water quality and caused the turnover and decline in the algal and cyanobacteria community. Following this rapid decline the abundance of algae and cyanobacteria remained low within the Lake Lanoto'o record for c. 1200 years. The recovery of the algal and cyanobacteria community at c. 5300 cal BP is coincident with an increase in the concentration of titanium and magnetic susceptibility within the lake sediments (Fig. 3), which represents increased in-wash of soil from the catchment as a result of a prolonged wetter period (Hassall, 2017), and likely resulted in a freshening of the lake.

The vegetation communities on Pacific islands have been shown to fluctuate in response to variations in past climate regime. On Tahiti, drier and cooler climates during the late Pleistocene (c. 45,000-41,000 years ago) saw an increased dominance of grasses, ferns and sedges (Prebble et al., 2016), while droughts associated with the Medieval Climate Anomaly (AD 800–1250/1150-70 cal BP) resulted in a loss of moisture demanding *Cyathea* ferns (Restrepo et al., 2012). In the Lake Lanoto'o core precipitation has been interpreted as being high between c. 5500 and 2500 years ago

(Hassall, 2017; Ti/inc curve Fig. 3). The elevated precipitation through this period does not appear to have resulted in any significant change in the vegetation community (Fig. 6). This suggests that while island ecosystems of the South Pacific are vulnerable to drought events, elevated precipitation on the levels experienced during the Holocene were not sufficient to drive species turnover or effect a major change in the balance of the community composition.

6. Conclusions

Despite low abundance the macrocharcoal record from Lake Lanoto'o detects the first human occupation of Upolu confirmed by direct archaeological evidence. The persistence of a strong charcoal signal through the Samoan Dark Ages suggests that people persisted on the island through this period. The close correlation between charcoal and human occupation of Upolu lends further weight to the argument that the investigation of ancient charcoal preserved in the sedimentary records is an effective method for detecting human occupation of ecosystems that do not naturally carry fire, even when the human populations are small.

Comparison of terrestrial and aquatic ecosystem change with the archaeological record and fire history of Upolu suggests that the arrival of humans on the island did not have a major impact on ecosystems in the central, higher elevation areas of the island. Our data support a simple model of decreasing human impact away from coastal areas towards high mountain environments with a gradual, but continual, process of opening up of the landscape; this model is in contrast to rapid, island wide, impacts identified on some other small islands. The inferred spatial gradient in human impact suggests that remote areas, such as Lake Lanoto'o, were buffered against human induced ecosystem change and are thus important sites of understanding native biodiversity.

The long-term ecological dynamics observed in the aquatic community of Lake Lanoto'o seems to be driven by internal (sedimentological) and external (climatological) factors, rather than by human factors. While the terrestrial ecosystems seem to be unresponsive to increased precipitation during the middle Holocene. The absence of major abrupt changes in the terrestrial ecosystem composition, and the likely natural drives of changes seen in the aquatic ecosystems, suggests that the early occupation of Upolu by humans did not have a significant ecological impact close to Lake Lanoto'o.

viii) **Tables**

Table 1: Summary of composition of major vegetation groups on Samoa (Olson et al., 2001).

Vegetation groups	**Key taxa**
Littoral	*Scaevola taccada* (Goodeniaceae), *Pandanus tectorius* (Pandanaceae), *Barringtonia asiatica* (Lecythidaceae), *Calophyllum inophyllum* (Calophyllaceae), *Pisonia grandis* (Nyctaginaceae), *Cocos nucifera* (Arecaceae)
Lowland rainforest	*Diospyros samoensis* (Ebenaceae), *Diospyros elliptica* (Ebenaceae), *Calophyllum inophyllum* (Calophyllaceae), *Dysoxylum samoense* (Meliaceae), *Dysoxylum maota* (Meliaceae), *Pometia pinnata* (Sapindaceae), *Planchonella samoensis* (Sapotaceae), *Syzygium* spp. (Myrtaceae), *Myristica fatua* (Myrtaceae)
Wet-cool montane rainforest	*Dysoxylum huntii* (Meliaceae), *Syzygium* spp. (Myrtaceae), *Weinmannia* spp. (Cunoniaceae), *Canarium harveyi* (Burseraceae), *Rhus taitensis* (Anacardiaceae), *Astronidium* spp. (Melastomataceae)
Cloud forest	*Reynoldsia pleiosperma* (Araliaceae), *Weinmannia samoensis* (Cunoniaceae), *Dysoxylum huntii* (Meliaceae) and *Coprosma savaiiensis* (Rubiaceae), *Dicranopteris linearis* (Gleicheniaceae), *Freycinetia storckii* (Pandanaceae), *Cyathea* spp. (Cyatheaceae)

Table 2: Radiocarbon ages obtained from Lake Lanoto'o, presented as ^{14}C years before AD 1950. The δ^{13}C is expressed as relative to the VPDB (δ^{13}C$_{VPDB}$) from Hassall (2017). SUERC = NERC Radiocarbon facility, East Kirkbride. BETA = Beta Analytic (Miami, USA), UCIAMS = Keck-CCAMS Group (California, USA).

Laboratory ID	Sample ID	Depth below sediment surface (cm)	Material	δ^{13}C$_{VPDB}$ (‰)	^{14}C uncalibrated age (yr BP)
UCIAMS-179834	LAN14-U2 24-25cm	24-25	Plant macrofossil	–25.9	540±15
SUERC-63980	LAN14-1-1 20-22cm	45-46	Bulk	–22.6	1096±35
BETA-439599	LAN14-1-1 31-32cm	56-57	Wood	–26.8	1630±30
BETA-439600	LAN14-1-1 45-46cm	70-71	Plant	–26.7	2570±30
SUERC-63981	LAN14-1-1 54-55cm	79-80	Bulk	–24.8	2453±37
UCIAMS-179835	LAN14-1-1 61-62cm	86-87	Plant macrofossil	–26.9	2700±20
SUERC-68884	LAN14-2-1 30-31cm	108-109	Bulk	–25.9	3607±44
SUERC-68885	LAN14-2-1 60-61cm	138-139	Bulk	–27.3	4497±48
SUERC-63982	LAN14-1-2 13-14cm	128-129	Bulk	–24.2	4064±35
SUERC-63983	LAN14-1-2 35-36cm	150-151	Bulk	–25.6	4638±36
SUERC-68886	LAN14-1-2 43-44cm	157-158	Bulk	–25.2	5071±48
SUERC-63984	LAN14-1-2 57-58cm	172-173	Bulk	–24.0	5768±38
SUERC-68887	LAN14-1-2 69-70cm	183-184	Bulk	–23.4	6128±59
SUERC-68891	LAN14-2-2 11-12cm	208-209	Bulk	–23.6	8092±77
SUERC-68892	LAN14-1-3 17-18cm	238-239	Bulk	–24.5	5879±56
SUERC-68893	LAN14-1-3 33-34cm	254-255	Bulk	–24.2	7794±74
SUERC-68894	LAN14-1-3 68-59cm	279-280	Bulk	–25.7	8462±82
SUERC-63985	LAN14-1-3 77-78cm	299-300	Bulk	–22.8	9440±40

ix) **Figures**

Figure 1: Location map. (A) Samoa lies in the South Pacific Convergence Zone (SPCZ) with a climate strongly influenced changes in the El Nino Southern Oscillation (ENSO) and the Inter-Tropical Convergence Zone (ITCZ). (B) Lake Lanoto'o lies at an elevation of 760m above sea level on the central ridge of volcanoes that comprise the Samoan Archipelago. (C) The lake is set within a volcanic crater in montane cloud forest (D). (E) The sediment core was raised from the deepest part of Lake Lanoto'o.

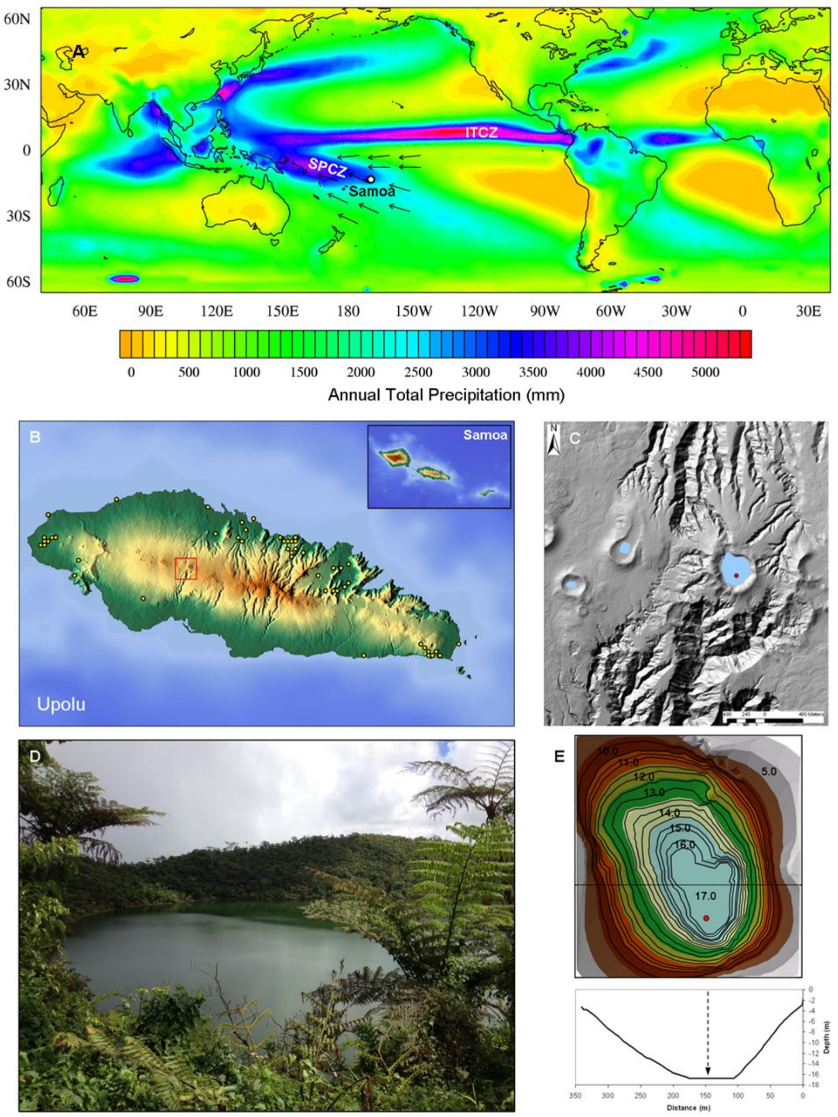


Figure 2: Age vs. depth model for Lake Lanoto'o sediment core. Green points are ^{210}Pb and ^{137}Cs CRS modeled ages. Blue symbols are bulk ^{14}C AMS dates with 2 sigma errors. All data are calibrated using SHCal13 in BACON 2.2 (Hogg et al., 2013; Blaauw & Christen, 2011).

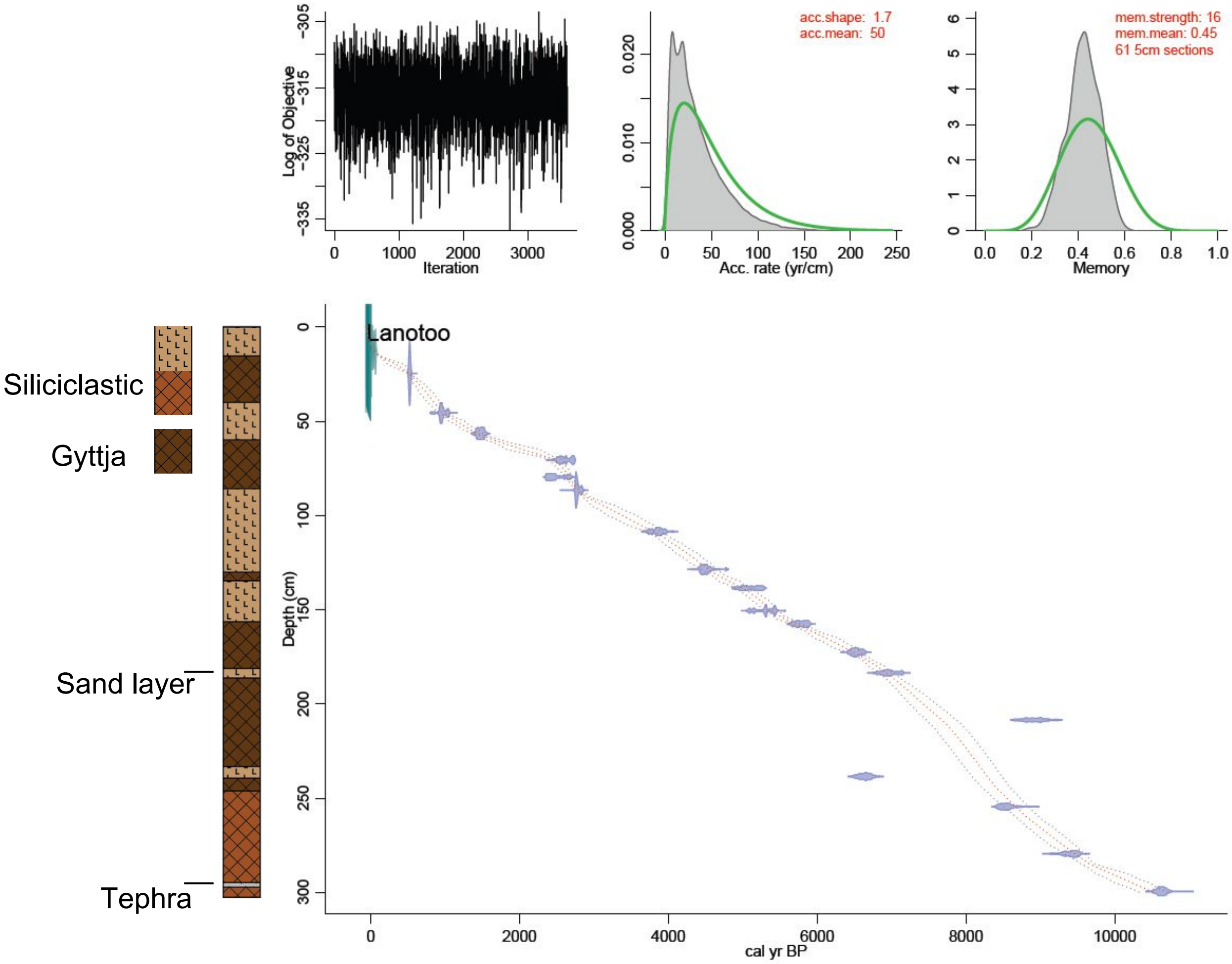


Figure 3: Physical properties and charcoal diagram from Lake Lanoto'o (Uplou, Samoa). Horizontal dashed grey line indicates the presence of siliceous sand (>160 µm; c. 6700 cal BP). Horizontal light grey bars indicate tephra layers (c. 10,063-9775, 3829-3576 and 81-62 cal BP). Horizontal dark grey bars indicated: (i) first archaeological evidence of Lapita people on Upolu c. 2900-2700 cal BP (Lap.; Petchy, 2001), and (ii) Samoan Dark Ages c. 1500-1000 cal BP (SDA; Davidson,1979; Green, 2002; Reith & Hunt, 2008). Vertical dotted lines on the charcoal data indicated 5 % of maximum abundance, values above 5 % are considered to exceed the background noise (following Kelley et al., 2011).

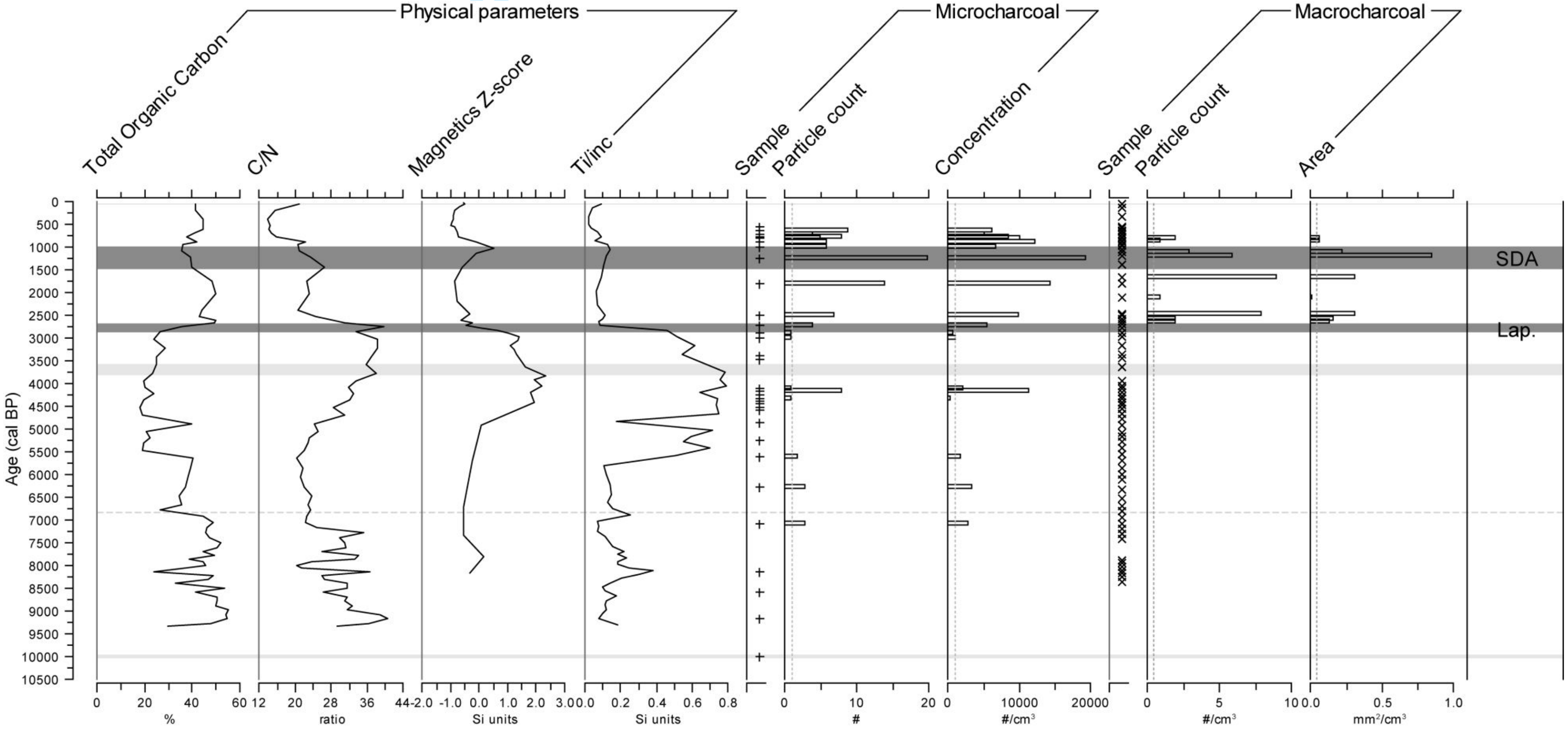


Figure 4: Summary diagram for pollen, spore, and macroscopic remains from Lake Lanoto'o (Uplou, Samoa). Pollen and spore taxa shown represent all taxa occurring at >5 % in at least one sample. For images of macroscopic remains see Plate 1. Notation follows Figure 3.

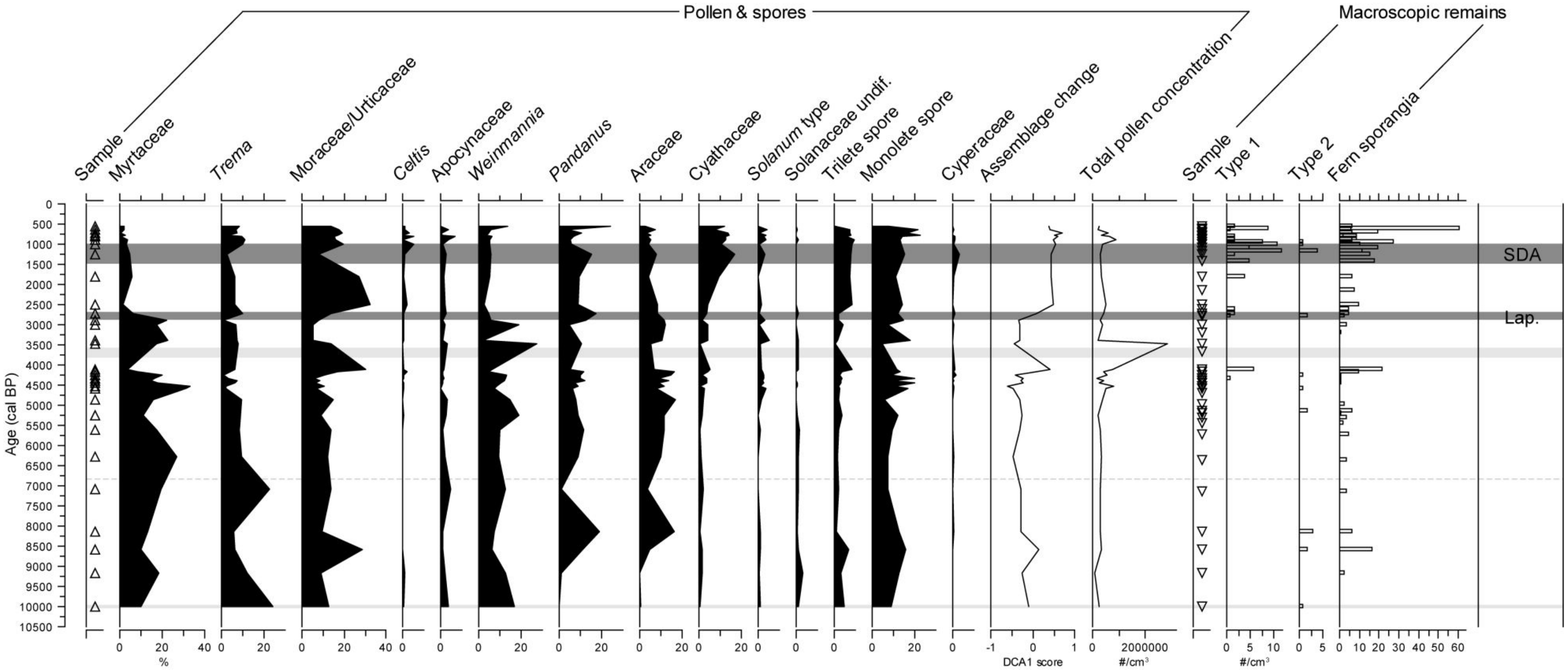


Figure 5: Summary algal and cyanobacterial diagram from Lake Lanoto'o (Uplou, Samoa). Notation follows Figure 3.

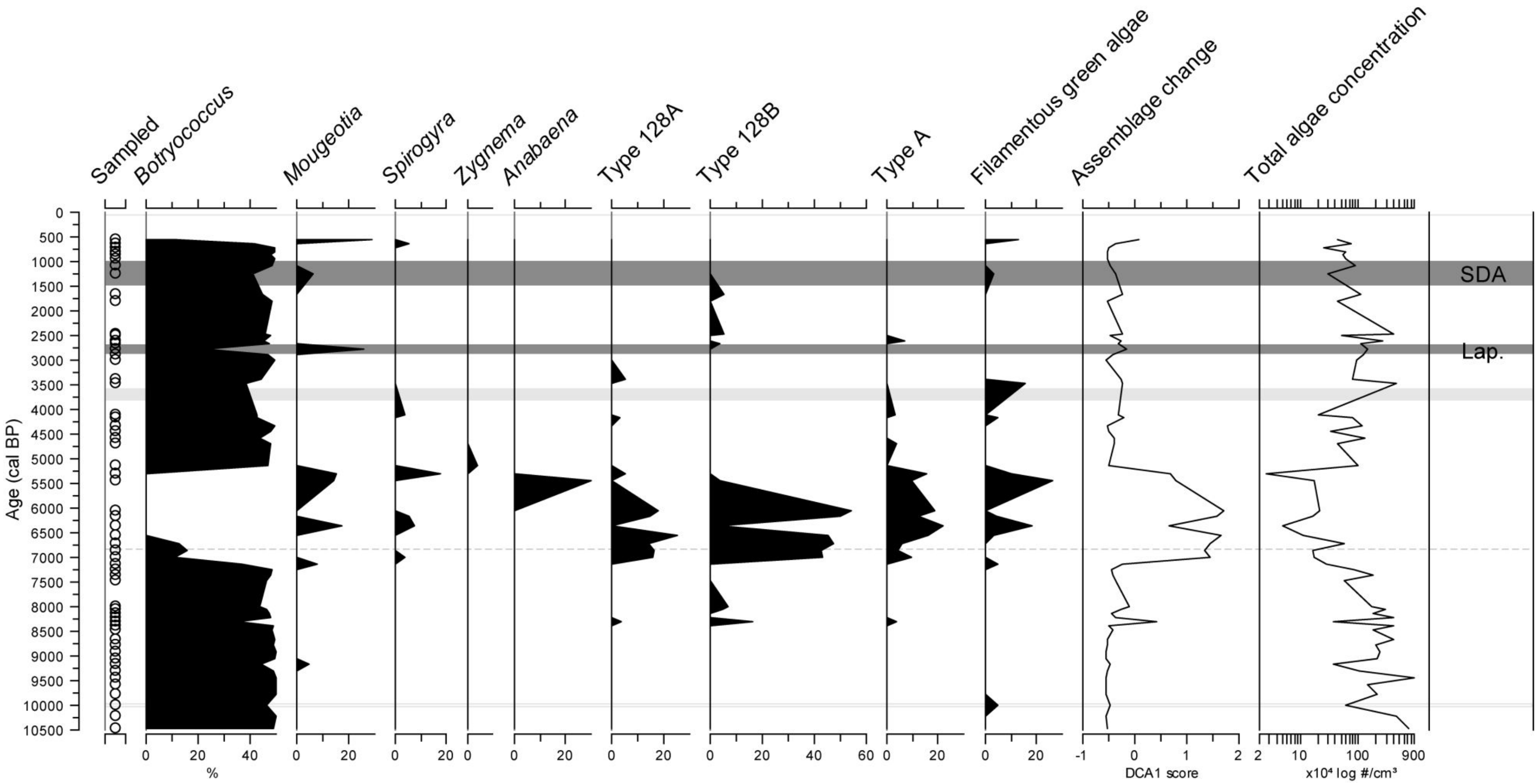
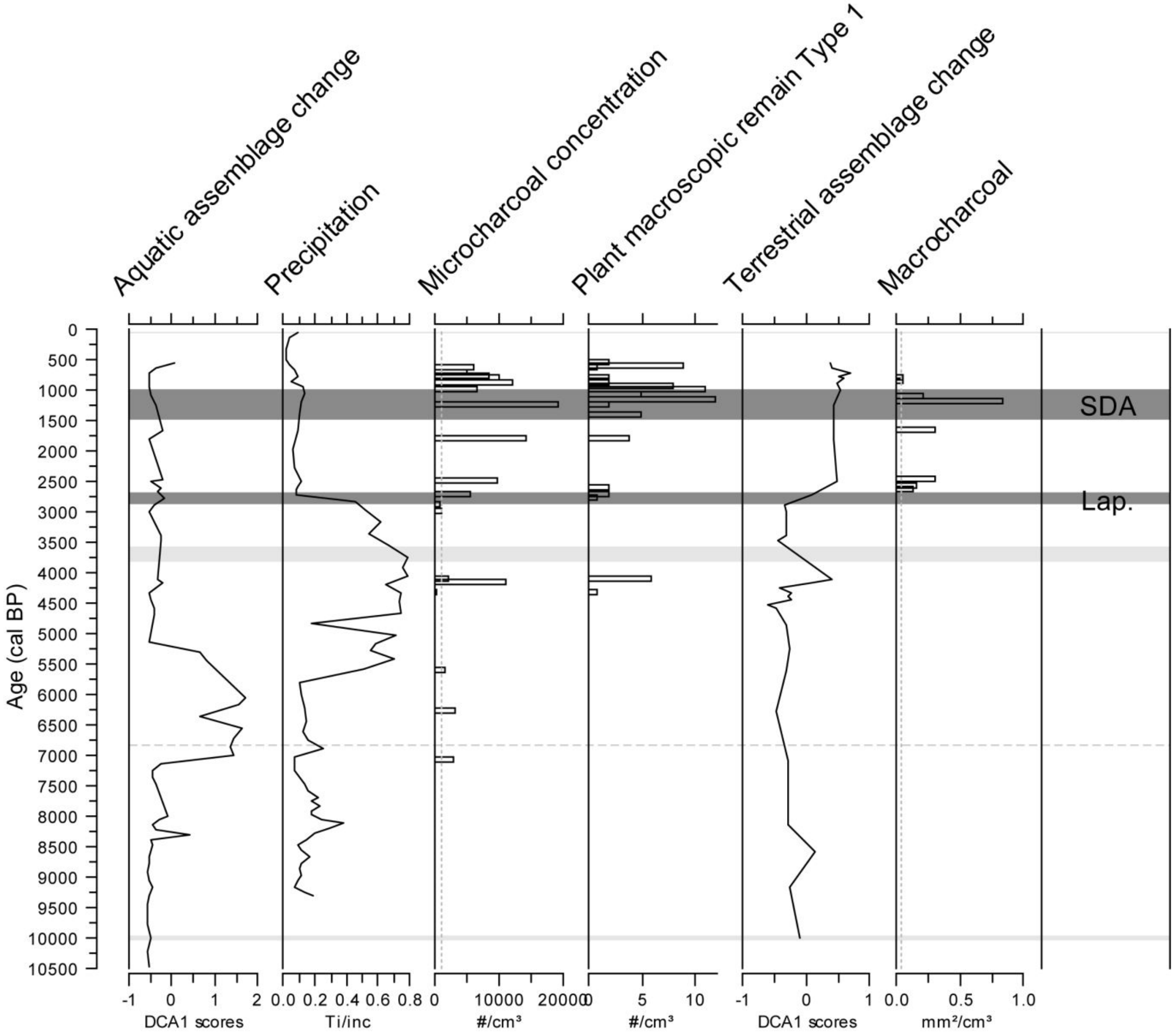


Figure 6: Composite diagram characterizing abiotic and biotic environmental change on Upolu (Samoa) over the last c. 10,500 years. Notation follows Figure 3.



x) **Data availability statement**

Data is deposited in Neotoma (https://www.neotomadb.org) and the Global Charcoal Database (http://www.paleofire.org/index.php); *add DOIs once obtained…*

xi) **References**

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xii) **Biosketch**

William Gosling is a palaeoecologist and biogeographer mainly focused on Quaternary environmental change in the tropics. He is Head of Department of Ecosystem & Landscape Dynamics at the University of Amsterdam, and more can be found about his research at www.ecologyofthepast.info.

Author contributions: The overall research program was led by PI DAS. The palaeoecological research was designed by WDG and CNHM. Sediments were collected and physical properties analyzed by DAS, JDH and PGL. Palaeoecological data were generated as part of an MSc Environmental Biology (Utrecht University) internship project (TD), a BSc Future Planet Studies (University of Amsterdam) dissertation project (ZvK), and two BSc Biology (University of Amsterdam) dissertation projects (KN, MNTB) all supervised by WDG and CNHM at the Institute for Biodiversity & Ecosystem Dynamics. Carbon and nitrogen data were generated by MJL and radionuclide and Itrax data by IWC and JDH. Cryptotephra data were generated by AJB. The manuscript was conceived and written by WDG, and developed with input from all co-authors.

xiii) **Appendix 1:** Abundant macroscopic plant remains recovered from sediments of Lake Lanoto'o (Upolu, Samoa): (a) Fern sporangia, (b) unknown seed Type-1, and (c) unknown seed Type-2.