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ANTHROPOGENIC BURNING, AGRICULTURAL INTENSIFICATION, AND LANDSCAPE TRANSFORMATION IN POST-LAPITA FIJI

Christopher I. Roos[1*], Julie S. Field[2], and John V. Dudgeon[3]

Slash-and-burn cultivation (swidden) is an important and extensive strategy among agriculturalists in Oceania. The length of the fallow period, in which non-cultivated vegetation is allowed to regrow, is critical to the sustainability of this strategy in tropical environments. Long fallow periods permit greater soil recovery and higher yields over the long term whereas shorter fallow periods drive cycles of soil degradation that ultimately result in a landscape that is too degraded for continued cultivation. Anthropologists recognize that decreasing swidden fallow times is a key form of agricultural intensification that may have shaped interpolity conflict and social complexity. Although it is easy to identify the degraded landscapes that are a legacy of this pattern today, it has been a challenge for archaeologists to identify the timing and rate at which such processes took place in the past. We use alluvial stratigraphic records of charcoal and stable carbon isotopes from a small drainage in Western Viti Levu, Fiji, to reconstruct the timing and rate of intensification of swidden agriculture from long-fallow clearing of native forest, to shorter fallow burning of secondary forest and grassland, to grassland conversion. Results suggest that swidden cultivation in the lower Sigatoka Valley did not commence until centuries after Lapita colonization (ca. 2950 cal BP). Early swiddening apparently used relatively short fallow periods coupled with residential mobility to sustain horticultural yields until mobility no longer became a viable option. Archaeological indicators of resource stress co-occur with persistent swiddening after 1450 cal BP, although these precede the collapse into degraded grassland conditions at 1000 cal BP. Archaeological evidence for conflict increase after landscape degradation, although emerging social inequalities only appear after centuries of degraded conditions and conflict.

Keywords: *human-environment impact, swidden farming, fire history, geoarchaeology, Oceania*

Investigating Agriculture and Island Ecology in Pacific Prehistory

In the western Pacific, archaeologists have argued for the occurrence of dramatic change to island ecology as a product of human action in the millennia after colonization by Austronesian people. These changes are thought to primarily be the activities of swidden farmers, who transformed the pristine hardwood and palm forests of Remote Oceania into open farmland (Kirch 1994; Spriggs 1981). Numerous questions have been generated in attempts to understand this process and these have been focused on the role of food production during the Lapita era of colonization—the resulting effects of landscape clearance and erosion on the food production of later centuries.

The use of fire for converting native vegetation to cropland, and its role in clearing fields and recycling nutrients bound in plant biomass, has also been

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implicated in the long-term political dynamics of Pacific societies (Haberle et al. 2001). Kirch (1994, 2010), in particular, has highlighted the role of dry land swidden cultivation in driving island-scale (and larger) competition and conflict. In order to be sustainable, swidden cultivation systems require large areas of potentially arable land to be in fallow. Although the net return rates of long-fallow swidden are relatively high, the overall productivity of these settings are limited by the temporal and spatial scale of fallowing. Intensification of swidden systems typically involves shortening the fallow cycle, thereby attenuating vegetation succession and soil recovery (Boserup 1965; Geertz 1963:33). As fallow periods shorten, the probability increases of crossing a systemic threshold into a permanently degraded state that is no longer productive enough to warrant cultivation. The abundance of fern- or grass-dominated degraded landscapes on Pacific islands at the time of contact with Europeans in the eighteenth and nineteenth centuries presumably attests to the ubiquity of these historical processes of swidden intensification (Latham 1983). Indeed, Kirch (1994, 2010) invokes the ancient degradation of dry land swidden systems as the precipitating factor in increased conflict and socio-political complexity. Despite the stated importance of swidden intensification and landscape degradation, we know very little about when, where, and how these processes unfolded, especially on larger islands.

For the most part, the detection of human impacts on island biota has been equated with the occurrence of charcoal in sedimentary deposits, changes in the relative frequency of pollen taxa associated with forests and grasslands, or penecontemporaneous charcoal and palynological changes (Athens and Ward 2001; Haberle and Ledru 2001; Hope et al. 2009; Latham et al. 1983). Closed basin wetlands, ponds, and estuaries, which serve as natural traps for aerial fallout of pollen, have served as primary collection sites for these records. Although these sedimentary deposits are ideal for preserving pollen, their vegetation records are mixed from large areas. As a result, it is difficult to infer where vegetation change documented in pollen assemblages occurred, thus making spatially explicit hypothesis testing impractical. This may be less problematic for small islands than for relatively large islands, wherein a diversity of micro-environments are present and where the spatial consequences of economic decision making and land-use create important historical contingencies.

To generate spatially explicit paleoecological records that are likely to yield evidence of human activities and impacts on key ecosystem properties, we undertook a terrestrial coring program along a transect from the coast to the interior within the greater Sigatoka Valley region of western Viti Levu, Fiji. As part of a larger project devoted to the study of subsistence transitions during the Post-Lapita era in Fiji, this coring program has generated sedimentary records from a series of small alluvial basins that are tributary to the Sigatoka River on Viti Levu. All of the watersheds are relatively small ($\sim$6.4–12.6 km^2) and vary in terms of their proximity to the coast (Figure 1). Unlike lacustrine or wetland settings, our terrestrial stratigraphic sequences are not ideal for the preservation of pollen. Rather, since landscape burning was the primary means by which ancient residents would have converted native vegetation into productive agricultural landscapes, and since fire, post-fire erosion, and post-fire succession are so important for understanding swidden intensification, we have concen-

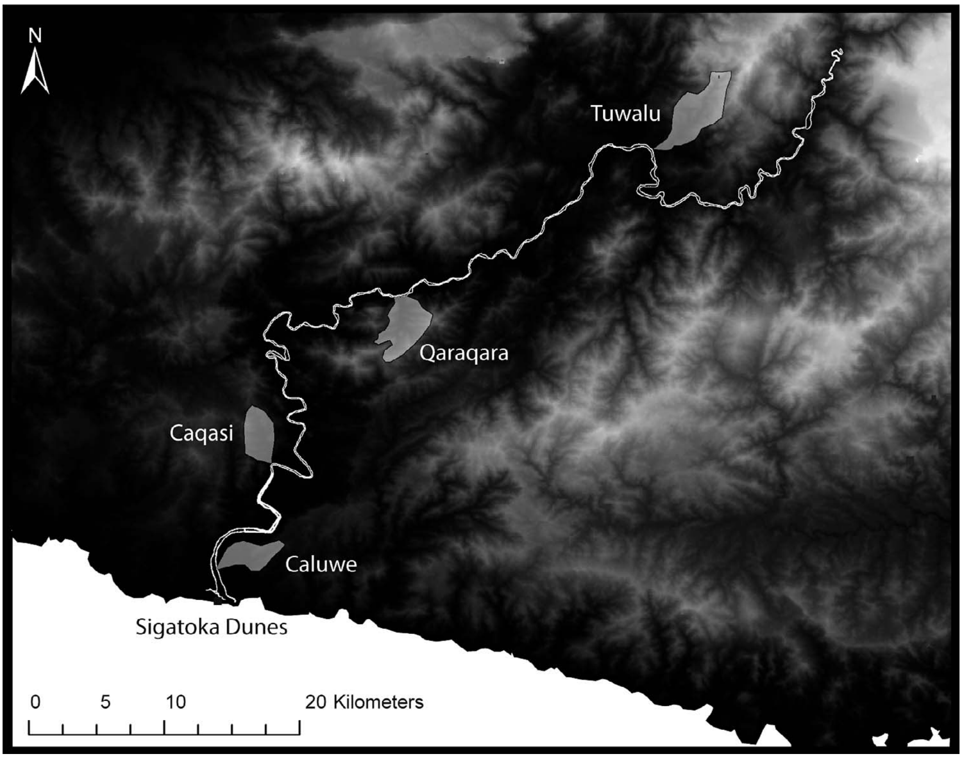

Figure 1. The location and outline of alluvial watersheds selected for the terrestrial coring program of the Post-Lapita Fiji Project.

trated our efforts on measuring sedimentary proxies of landscape fires (charcoal concentration and flux), post-fire erosion and sedimentation rates (cm/yr), and the relative contribution of early successional plants to the soil carbon pool (stable carbon isotope ratios). Because virtually all of these sediments are derived from the alluvial watershed, we can link well-dated transitions in these proxies to specific parts of the landscape where and when they occurred.

Here we present the results of the analysis of terrestrial records from the Caluwe Creek basin, a small watershed that lies within 4 km of the well-known Lapita and post-Lapita site of Sigatoka Dunes (Birks 1973; Burley 2003, 2005; Burley and Edinborough 2014; Marshall et al. 2000; Figure 2). The results of these analyses have implications for the history of swidden gardening in early Fiji, the impact of anthropogenic change on Fijian ecology, and any recursive impacts that the legacies of swidden intensification and landscape degradation had on socio-political dynamics of Fijian communities (Field 2004, 2005).

The Sigatoka Valley, Fiji

The Sigatoka Valley, located in the western portion of the island of Viti Levu, Fiji, is an ideal location for the study of anthropogenic landscapes, swidden

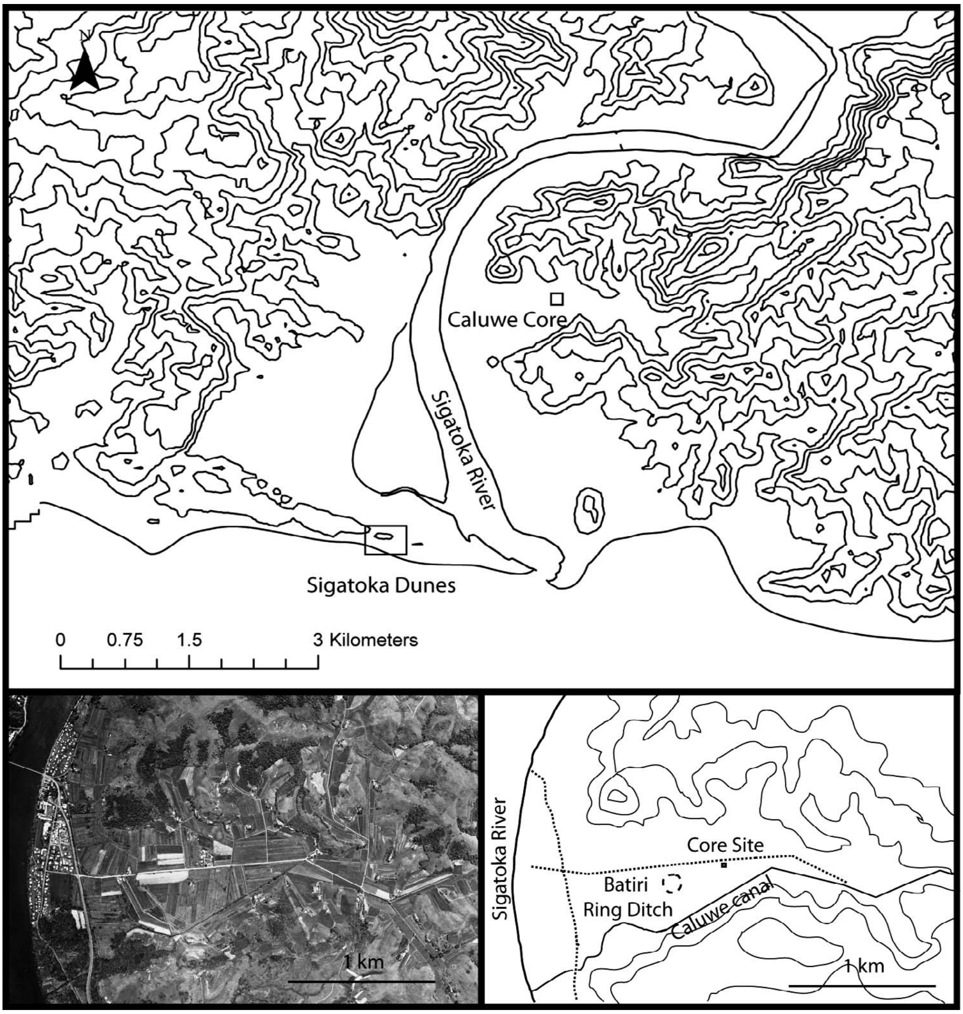

Figure 2. The location of the Caluwe coring site within the Caluwe Creek drainage and its proximity to the Sigatoka Dunes (top) and Batiri (bottom right) archaeological sites. Modern cultivation and landscape vegetation communities for the watershed can be discerned in the historic aerial photograph (bottom left).

agriculture, and Pacific Island socio-ecological dynamics. As a continental island, Viti Levu is geologically complex and contains deposits and formations that originated during periods of uplift and volcanism between 33 and 10 mya. Subsequent erosion and redeposition has produced deep deposits of alluvium, most of which post-date the Last Glacial Maximum (ca. 18,000 BP) after which rapid sea level rise drove valley aggradation until peak marine transgression between 5000 and 3000 BP (Nunn 1990). At 18° S, Fiji enjoys the warm sunny climate that typifies the Southwestern Pacific, which also makes it suitable for the cultivation of the staples of Pacific Island agriculture, taro (*Colocasia esculenta*) and Asian yam (*Dioscorea* spp.). Importantly, Viti Levu falls within the belt of southeasterly tradewinds that generates strong geographic and seasonal variation in rainfall, with the majority of the precipitation in the (Austral) summer months, a pattern that is particularly pronounced on the leeward (western and northern) side of the island. On an interannual to decadal scale, Fiji falls within the region that is strongly affected by El Niño Southern Oscilation (ENSO), resulting in exacerbated (Austral) winter drought during warm phase (El Niño) events (Hilton 1998; Parry 1987; Salinger et al. 1995). Prior to human colonization and the introduction of invasive species from other subtropical regions of the world, these climate dynamics supported palm forests (*Metroxylon*) along the coast and the interior and also hardwood forests (*Casuarina* and *Santalum*) in the higher elevations (Hope et al. 2009; Watling 2005). Palynological studies have suggested that the leeward side of Viti Levu, where the Sigatoka Valley is located, was originally forested (although it may have been a mosaic of mesic and tropical dry forest types, sensu Keppel and Tuiwawa 2007), but was transformed into a lightly wooded grassland at some point during the last three millennia following human colonization (Hope et al. 2009; Southern 1986).

The oldest Lapita settlement in Fiji is the site of Bourewa, which is located to the west of the Sigatoka delta and dates to 2950–3050 cal BP (Nunn et al. 2004). Human presence in the Sigatoka Valley proper was first noted in the 1960s when Lapita ceramics were identified at the site of Sigatoka Dunes (Green 1963). Subsequent excavations and analyses of the deposits at the Sigatoka Dunes have firmly dated the Lapita occupation to 2600–2700 cal BP and also documented a sequence of occupations and abandonment of the Sigatoka delta and dune area between 1450–1250 cal BP, with less than 50 years of dune activity separating the two occupations (Burley 2003; Burley and Edinborough 2014). Importantly, the refinements to the so-called Mid-Sequence occupations of the Level 2 paleosol at the Sigatoka dunes provide a refined chronology for the onset of major dune building with reworked terrigenous sediments that Dickinson links to enhanced inland erosion and sediment transport by the Sigatoka river (Dickinson et al. 1998).

Faunal remains and the study of skeletons at this and other Lapita-era sites in the southwestern Pacific have indicated that the initial Austronesian colonists were broad-spectrum foragers and subsisted on marine and terrestrial resources and domestic animals (Kinaston et al. 2014a, 2014b). There have been hints, however, of food production by Lapita peoples in the form of archaeologically preserved starch in sedimentary deposits (Horrocks and Nunn 2007). It seems certain that food production was practiced, at least at a low level, following the initial colonization of new islands. The rate of its increase, and the role of food production in the transformation of islands, have been the more elusive questions pursued by archaeologists. For the Sigatoka Valley, previous work has indicated a human presence in the interior by 2000 BP (Field 2004), but the purpose of that visit, and how it relates to later population settlement and demographic growth, are yet undetermined.

The establishment of fortified settlements in the interior that were in high, defensible locations began by 1350 BP. A further episode of expansion of fortified settlements into marginal environments coincided with the emergence of socio-political complexity and inter-group competition after 1000 BP, with greatest evidence for socio-political differentiation in the last five centuries. More recently, Burley (2013) has suggested that ceramic data and a sharp occupational discontinuity within the Sigatoka Dunes Level 2 paleosol is indicative of the intrusion of a migrant population that colonized the region ca. 1350 cal BP. Based upon ceramic and architectural traits, Burley (2013) suggests these people came from the archipelagoes to the west (Vanuatu or New Caledonia).

Geoarchaeological Evidence for Swidden Intensification

Swidden cultivation, also called "slash-and-burn" horticulture, is a shifting horticultural strategy in which the existing vegetation is burned to open the canopy and recycle nutrients to the soil that had been incorporated into living plant biomass (Conklin 1961). This is the so-called "ash bed effect," wherein key nutrients, such as phosphorus (P), potassium (K), and nitrogen (N), are liberated from plant tissues by combustion, effectively fertilizing new growth (Debano et al. 1998:108–121). Depending on the combustion conditions, this conversion can be extremely inefficient with some nutrients lost to volatilization, especially at higher temperatures. When there is a net increase in nutrient availability it is often short-lived and cultigen productivity typically declines after the first three to five years of cultivation. The long-term success of swidden farming is dependent upon the amount of time that a cultivated field is allowed to rest and regenerate natural vegetation between cultivation episodes. These fallow periods allow for plant succession to restore elements of the soil nutrient pool (e.g., to fix nitrogen) and to store some of the readily available nutrients in living plant biomass (Juo and Manu 1996). Longer fallow periods provide greater vegetative and soil recovery but require larger areas of cultivation per person. Shorter fallow periods reduce the per capita area needed for cultivation but run the risk of crossing a systemic threshold where shorter recovery times result in enhanced rates of soil degradation through nutrient declines and physical soil loss.

From a geoarchaeological standpoint, there are a number of biological, chemical, and physical sedimentary byproducts that are influenced by properties of the swidden cultivation system. A direct indicator of burning vegetation to establish or clear fields is the production of charcoal, a product of incomplete biomass combustion (Scott 2010). However, charcoal accumulations in soils or sedimentary deposits are a complicated proxy for landscape burning. Coarser fuels, such as stands of timber, have lower surface area to volume ratios and tend to combust less completely and produce larger quantities of charcoal during landscape fires. Fine fuels, including grasses and annual herbs and forbs, have greater surface area to volume ratios, thus combusting more completely and producing lower volumes of particulate byproducts (DeBano et al. 1998:27). As a result, long-fallow swidden systems that allow woody vegetation to regenerate and grow for prolonged periods before being cultivated again should produce an increase in sedimentary or soil charcoal. Spatial extensification of swidden systems or decreases in fallow time that still allowed succession to dense, woody vegetation would be expected to produce further increases in soil or sedimentary charcoal. However, a reduction in fallow time such that grasses and other fine fuels remained a significant component of the fuel load may not produce an increase in overall charcoal production, even if there were more area burned per unit of time, because the finer fuels have both lower biomass and burn more completely than woody fuels (Marlon et al. 2006; Roos 2008).

Swidden cultivation would also be expected to impact sediment availability from hillslopes by exposing soil to rain splash and surface runoff. The cumulative area in cultivation within a basin is important, as is the size and continuity of cultivated patches for concentrating surface flow. Thus the size of individual fields and their spatial pattern will have important impacts on sediment yield and erosion within cultivated watersheds. Swidden intensification, through its impacts on plant succession, however, can extend the post-cultivation period of enhanced sediment yield in addition to any impacts on the overall scale and pattern of cultivated areas. The eroded material will accumulate in sedimentary basins and the rate of accumulation will be influenced by the rate of sediment yield, among other factors.

Although pollen records indicate that the native vegetation on the leeward side of Viti Levu was dominated by palms and hardwoods (Hope et al. 2009), native tropical grasses were also present before colonization by Lapita people ca. 3000 BP. Because of the benefits offered in water-use efficiency, tropical grasses (and other herbaceous, dry land plants) evolved versions of the C4 photosynthetic pathway that discriminates less against CO_2 with the heavier isotope ^{13}C relative to plants that use C3 photosynthesis (woody plants throughout the world and some extratropical grasses). The differences in these photosynthetic pathways results in divergent ratios of the stable isotopes of ^{12}C and ^{13}C in the biomass of C4 (ca. –13‰) versus C3 (ca. –25‰) plants. Because there is no fractionation of the carbon isotope composition of plant matter as it decays, soil organic carbon pools reflect the weighted average of the carbon isotope ratios of the plants that grew on them (Nordt 2001). In tropical swidden systems, the contribution of C4 grasses to the soil carbon pool is related to their abundance (by mass) on the landscape and, by extension, the length of fallow periods permitted within the cultivation system. This should be reflected in the stable isotope ratios of the soil in cultivated areas as well as in sedimentary contexts wherein eroded and redeposited topsoil from the surrounding watershed is accumulating.

On many tropical Pacific islands, degraded landscapes are predominantly covered with *Dicranopteris linearis* and *Pteridium esculentum* ferns. On Viti Levu today, these degraded landscapes (locally referred to as *talasiga*, or "sun-burnt land") are predominantly introduced tropical grasses (*Pennisetum polystachyon, Heteropogon contortus,* and *Imperata conferta*), although one native grass (*Miscanthus floridulus*) persists in these settings (Parry 1987). *Dicranopteris* ferns are C3 plants, so short-fallow cultivation with succession dominated by ferns would not be distinguishable on the basis of soil stable carbon isotopes. However, pollen records indicate robust grass (*Poaceae)* pollen production over the last 2000–3000 years in parts of Viti Levu (Hope et al. 2009), suggesting that *Miscanthus* or other, now extirpated grass species may have been more common in *talasiga* prior to European introduction of invasives. Additionally, sugar cane (*Saccharum* spp., a C4 grass) was cultivated for an unknown period prior to European contact and may have contributed to soil carbon isotope ratios. In summary, we expect long-fallow swidden cultivation to have highest (and potentially most variable) charcoal fluxes, lower sedimentation rates, and more depleted (more negative) stable carbon isotope ratios than short fallow cultivation. We use the most recent sediments as a guide for interpreting the emergence of degraded *talasiga* conditions in a manner analogous to the direct historical approach used by archaeologists in North America (Steward 1942).

Methods

In July 2013, we used a 3 cm diameter percussion coring rig to collect a paired set of ~6.3 m cores (CAL-1 and CAL-2) in 90 cm increments from terrestrial sediments and soils within the sedimentary basin of Caluwe Creek (Figure 2). Until the late 1990s, the cored area had been a plowed, commercial sugar cane field, although it is currently not in production. The coring location is less than 300 m northeast from the ring-ditch fortified late pre-contact village of Batiri that has been radiocarbon dated to 1–315 cal BP (Field 2004), suggesting that the floodplain stabilized by sometime in the last 300 years. Caluwe Creek drains into the Sigatoka River roughly 2.4 km upstream from the beachfront on the delta plain. The groundwater table was shallow (~1.2 m below the surface) at the time of coring, although the modern creek has been canalized and lies at a depth greater than 1.5 m below the coring surface roughly 200 m to the southeast. The shallow water table meant that much of the core was saturated, resulting in differential compaction between the two cores that were separated horizontally by less than 40 cm. The cores were collected in capped polyvinyl tubes and taken to the field base camp where they were opened in tandem, photographed, and described using standard pedological and sedimentaological nomenclature. After description, samples were collected continuously in 5 cm intervals or at stratigraphic boundaries when appropriate (N = 97 samples for CAL-2; N = 94 samples for CAL-1). The least compacted of the two cores (CAL-2) was used to determine recovery depths (485 cm in total, or roughly 77% compaction of downhole coring depths) and shared lithostratigraphic and/or pedostratigraphic boundaries in the two cores were used to align them for sampling. Samples were shipped to the Geoarchaeology Lab at Southern Methodist University where they were inventoried, oven-dried at 60 °C, and ground and sieved at 2 mm to isolate the < 2 mm "fine fraction" for subsequent analysis. The masses of both coarse and fine fractions were recorded and any organic sediments in the coarse fraction were collected.

With the exception of samples from 310–325 cm, all measurements were done on 5 cm interval samples continuously. Between 310–325 cm, the coarse fraction (> 2 mm) exceeded 37%, limiting the amount of fine fraction material available for analysis. The coarse fraction at these depths was entirely composed of fragments of wood, probably palm but as yet unidentified. We measured soil pH using a 1:1 sediment to deionized water slurry for 96 of the 97 samples. Particle size analysis (PSA) was done with a stepped wet-sieving method to separate sands from silts and clays (63 μm sieve) followed by gravimetric estimates of the relative silt and clay content (Janitsky 1986). The wet-sieved sand fraction was dried, weighed, and sorted into USDA size fractions using nested screens on a sonic sifter. The fractions of silt (62.9 μm to 4 μm) and clay (< 4 μm) were estimated using a pipette method and Stoke's Law. PSA was done on all samples with less than 37% coarse fraction (N = 94) on 20 g sub-samples that had been decalcified with 0.5N HCl, oxidized with reagent grade (33%) H_2O_2, and deflocculated with 5% sodium metaphosphate solution. The proportions of sand, silt, and clay are presented as % by mass.

Charcoal concentrations were measured gravimetrically using a modified version of the HNO_3 digestion and loss-on-ignition (LOI) method described by Winkler (1985). This method allows for simultaneous estimates of unburned and burned organic matter by monitoring mass loss after HNO_3 digestion and after LOI of the treated sample. In Winkler's (1985) original study, this method systematically underestimated the actual charcoal content by ~20%, a proportion that has been corroborated by internal laboratory experiments (Roos, unpublished data). We have added an HCl pretreatment step to remove any secondary carbonates in an effort to improve the precision of the HNO_3 digestion estimates of organic matter. Estimates of oxidizable organic matter is presented as % weight loss after HNO_3. Estimates of charcoal concentration are reported as mg/g.

Stable carbon isotopes of total soil organic matter were measured on the decalcified < 125 μm fraction of all samples to physically remove any rootlets and chemically remove any secondary carbonates or calcareous very fine sands. Powdered, pretreated samples were measured at Idaho State University on an Elemental Analyzer-Isotope Ratio Mass Spectrometer (EA-IRMS) for %C, %N, and stable isotopes of C and N, although we only report on the C isotopes here. Stable carbon isotope ratios were calculated relative to the Vienna equivalent of the Pee Dee Belemnite and are expressed as ‰. Estimates of the contribution of C4 biomass to carbon pools measured in the samples (probably a mix of local/authigenic and detrital/allogenic organic carbon) were calculated using a conservative mass balance equation that assumed idealized C3 (–25‰) and C4 endmembers (–13‰) but did not assume any additional depletions by wetland or closed canopy C3 communities (Nordt 2001).

Age-control was provided by AMS radiocarbon dating of burned and unburned plant tissues. From lithological unit I, coarse sand- to granule-sized pieces of unburned wood and leaves (unidentified, but probably *Metroxylon*) were pretreated with a standard Acid-Base-Acid protocol. Coarse sand-sized or larger charcoal and unburned organics were relatively rare in the sediments of lithological unit II (see below). As a result, an analogous pretreatment protocol (hot HCl followed by hot HNO_3) for the Winkler measurement of charcoal was used to pretreat bulk sediment for radiocarbon measurement of the residual, unoxidized charcoal fraction of the sediment. A total of 16 AMS determinations have been made from CAL-2 and one AMS determination has been made from CAL-1. Interpretation of the resultant ages (Table 1) was guided by the assumptions that: 1) charcoal dates always provide *terminus post quem* ages (Dean 1978) and 2) older charcoal that had been in sedimentary or soil storage upstream or upslope from our coring localities means that periods of enhanced hillslope erosion were likely to bias aggregated charcoal dates towards older ages. In short, we rejected bulk radiocarbon ages that were older than those below them because of the likelihood that they contained legacy charcoal from soil storage that does not date to the age of the deposit, but rather to some prior period. Eight of these radiocarbon determinations were then used to build an age-depth model using a smoothing spline in the CLAM software package for R (Blaauw 2010), with a hiatus identified at the boundary between lithostratigraphic units I and II and the assumption that the floodplain likely stabilized within 100 years either side of 150 BP.

Results and Interpretation

The deposits at CAL-1 and 2 can be divided into two major lithostratigraphic units (Figure 3). Unit I extends from 295 cm (compacted depths, unless otherwise noted) to the base of the core. Unit I consists of strongly acidic, organic-rich, sandy muds with hints of parallel bedding. Sands are moderately well sorted and generally make up more than 50% of the inorganic sediments. Unit II generally consists of neutral to slightly acidic massive muds. Decimeter-scale upward fining sets are discernible in the PSA data, although they were not discernible in the field.

The deposits at CAL-1 and 2 can also be divided into four major pedostratigraphic units. The organic-rich, sandy muds of lithostratigraphic unit I form the parent material for two buried soils. AChb3 is a weakly expressed organic soil primarily identifiable on the basis of the pedogenic destruction of bedding features. AChb3 is buried by finer grained, neutral sediments, large pieces of unburned wood, and sandy muds that form the parent material for a weakly expressed buried A horizon (Ab2). Ab2 was buried by inorganic terrestrial sediments of lithostratigraphic unit II that form the basis for two pedostratigraphic units in the upper 295 cm of the core. The lowermost of these soils has a thin (~10 cm) buried A horizon (Agb1) above weakly pedogenized floodplain deposits (Bgb2). The modern soil has an overthickened A horizon (120 cm thick) over weakly pedogenized floodplain deposits (Bg). Both the surface soil and the first buried soil have been substantially altered by redoximorphic (gleying) conditions from the perched water table.

Radiocarbon measurements (Table 1; Figure 3) indicate that lithostratigraphic unit I and the soils therein formed between roughly 7200–2800 cal BP. This period of accumulation coincides with major eustatic sea level rise and is probably driven by changes in the local base level (the Sigatoka River), which is in turn driven by sea level rise. Local relative sea level probably began to drop with marine regression ca. 3000 cal BP and the declining sedimentation rate and the formation of Ab2 after 4000 cal BP; the hiatus after 2800 cal BP (Figure 4) probably reflects the slowing and cessation of base-level driven aggradation.

Major overbank flooding with inorganic sediments begins in earnest after this time, although the precise date is difficult to determine because older charcoal redeposited within these sediments produces an anomalously early date for aggregated charcoal (see Table 1). On the basis of the extrapolation of the age-depth model (Figure 4), this probably commenced between 1730–1910 cal BP

Table 1. Radiocarbon determinations for stratigraphic cores in the Caluwe Creek basin. Calibrations were done with Calib 7.0 using the SHCal13 dataset (Hogg, et al. 2013). All calibrated dates are rounded to the nearest half decade. (1) Bulk charcoal date using HCl-HNO3 pretreated sediment to isolate the oxidation resistant "Winkler" charcoal fraction; (2) Acid-Base-Acid pretreated individual charcoal piece (unidentified); (3) Acid-Base-Acid pretreated individual unburned palm leave or frond fragment (unidentified); (4) Acid-Base-Acid pretreated individual unburned palm wood fragment (unidentified).

Sample #	Depth (cm)	Lab #	Material and pretreatment	Radiocarbon age ^{14}C BP	Calibrated date BP (2σ)	Interpretation	Included in age-depth model?
2.005	20–25	Keck 142261	1	Post-bomb	NA	Modern charcoal in the plowzone	No
2.010	45–50	AA103077	2	>45,2000	NA	Redeposited pre-glacial charcoal eroded from hillslope soils	No
2.020	95–100	Keck 151948	1	1120±20	930–1055	Primary charcoal from swidden cultivation in alluvium	Yes
2.022	105–110	Keck 151949	1	1205±20	980–1170	Primary charcoal from swidden cultivation in alluvium	Yes
2.033	160–165	Keck 142262	1	2365±25	2210–2435	Primary charcoal from swidden cultivation in alluvium with some reworked older charcoal	No
2.033	160–165	Keck 151950	1	3195±25	3260–3450	Primary charcoal from swidden cultivation in alluvium with some reworked older charcoal	No
2.037	180–185	Keck 151951	1	2120±20	2000–2140	Primary charcoal from swidden cultivation in alluvium with some reworked older charcoal	No
2.041	200–205	Keck 151953	1	2665±20	2725–2780	Primary charcoal from swidden cultivation in alluvium with some reworked older charcoal	No
2.044	215–220	Keck 142263	1	1655±25	1425–1564	Primary charcoal from swidden cultivation in alluvium	Yes
2.051	250–255	Keck 142264	1	1800±25	1595–1725	Primary charcoal from swidden cultivation in alluvium	Yes
2.057	280–285	Keck 151954	1	3365±25	3475–3635	Primary charcoal from swidden cultivation in alluvium with some reworked older charcoal	No
1.060	295–300	Keck 151919	3	2820±20	2790–2950	Preserved leaf fragment in primary context in wetland soil	Yes
2.063	310–315	AA103078	4	4849±45	5330–5645	Preserved wood fragment in secondary context in wetland soil	No
2.069	340–345	AA103079	4	4752±45	5320–5585	Preserved wood fragment in primary context in wetland soil	Yes
2.083	410–415	AA103080	4	6043±48	6695–6975	Preserved wood fragment in primary context in wetland deposit	Yes
2.097	480–484	AA103081	4	6239±48	6965–7250	Preserved wood fragment in primary context in wetland deposit	Yes

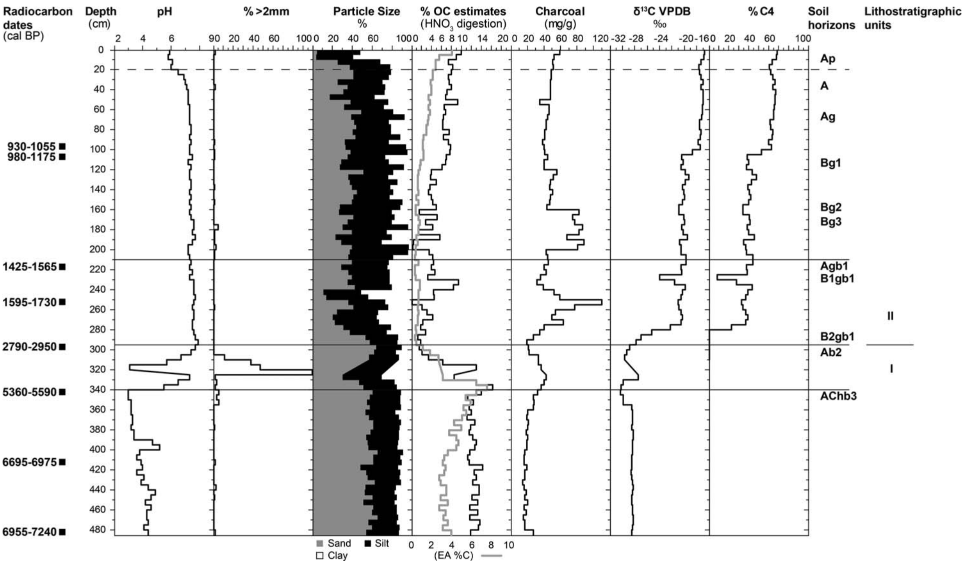

Figure 3. Stratigraphic plot of geoarchaeological and paleofire data by depth below the coring surface.

(95% confidence interval). Floodplain sedimentation must have slowed ~1500 cal BP to enable the formation of Ab2 (Figure 3) but resumed after less than a century at probably similar rates of accumulation until between 70–400 cal BP (95% confidence interval from age-depth model), with probable slowing of the sedimentation rate over the last 1000 years to enable the formation of the overthickened modern A horizon over that interval.

With the exception of the parent material for Ab2, charcoal concentrations are very low and stable (~20 mg/g) in lithostratigraphic unit I. This could indicate regular contributions of small amounts of charcoal from the surrounding watershed or from aerial fallout from regional fires. Alternatively, this low level of oxidation-resistant carbon could be a reflection of the anoxic conditions that have preserved unburned plant tissues in these sediments, inflating the apparent "charcoal" signal that may actually be oxidation resistant but unburned (e.g., leaf cuticle). Alternative measurements (e.g., ^{13}C Nuclear Magnetic Resonance [NMR] spectrometry) may be required to adjudicate between these alternatives, but if the Winkler charcoal estimates are fire-derived, then it would suggest a regular, if small, contribution of fires to the natural, pre-human ecology of the area (cf. Nunn and Kumar 2004).

Stable carbon isotopes from lithostratigraphic unit I, however, suggest that within the catchment for sediments at CAL-1 and 2, disturbance played little, if any, role during its accumulation. Stable carbon isotopes are extremely depleted within these sediments and soils (–28 to –30‰), consistent with a strong depletion effect created by a firmly closed forest canopy. The isotope results suggest that with a consistently closed canopy, the apparent charcoal in these deposits may more likely be unburned but oxidation-resistant organic molecules.

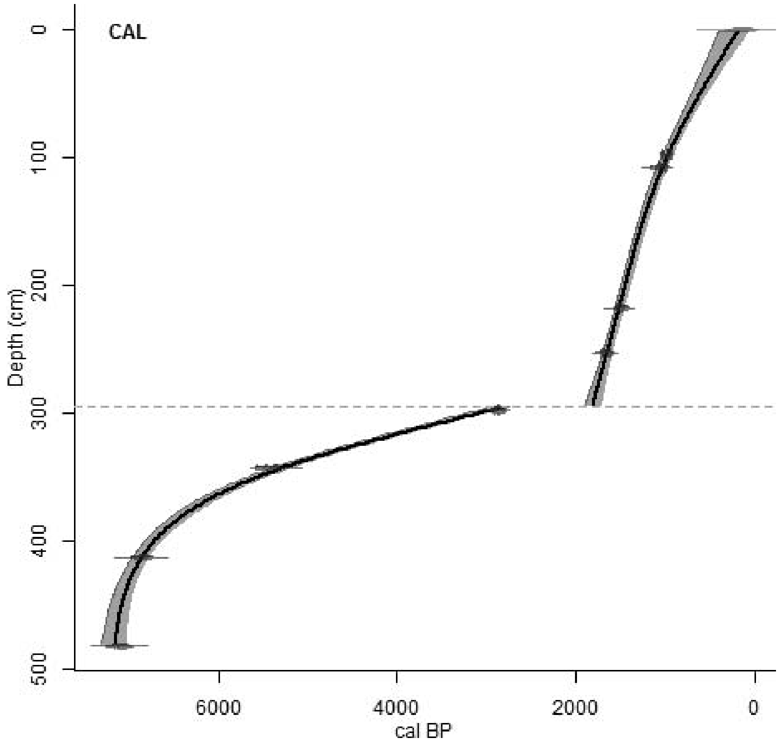

Figure 4. Age-depth plot for interpolated cal BP dates for the Caluwe (CAL) cores.

By contrast, the inorganic sediments in lithostratigraphic unit II are charcoal rich (> 40 mg/g) and display isotopic signatures (–17 to –24‰) of substantial canopy openings and contributions of C4 plants to the local (authigenic) and detrital (allogenic) carbon pools. Radiocarbon determinations on bulk charcoal and sediment include several dates that are out of stratigraphic order, particularly from the rapidly accumulating charcoal-rich sediments that bury Ab2 and Ab1. This suggests substantial erosion of hillslope soils that included archived, older charcoal that was deposited with swidden charcoal on the floodplain. A radiocarbon infinite determination on the one piece of granule-sized (> 2 mm) charcoal collected from lithostratigraphic unit II indicates that the surrounding hillslope soils had been relatively stable since before the last Glacial period.

Two major peaks in charcoal concentration (> 70 mg/g) occur in the floodplain sediments that bury the Ab2 and Ab1 soils. These co-occur with evidence for hillslope erosion (i.e., radiocarbon inversions) and isotopic evidence for substantial C4 plant communities. However, charcoal concentrations decline in the Ab1 soil, along with evidence for reduced C4 plant communities ca. 1500 cal BP. Charcoal concentrations stabilize around 50 mg/g more after peak biomass burning and erosion buried the Ab1 soil, but isotope ratios indicate another expansion of C4 grasslands to levels comparable to those at European contact at 1000 cal BP.

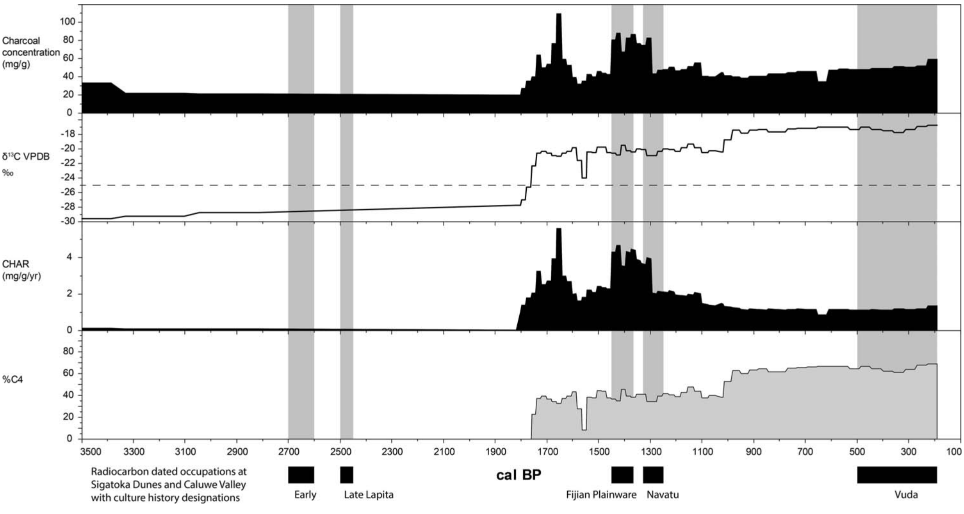

Figure 5. Charcoal concentration, stable carbon isotope ratios, charcoal accumulation rates (CHAR), and mass-balance estimated percentage of C4 plants contributing to the organic carbon pool for the watershed since 3500 cal BP. Vertical bars denote radiocarbon dated occupations of the Sigatoka Dunes and the Caluwe Creek drainage basin and their culture history designations.

Discussion

In the context of the local (Sigatoka Dunes and Batiri) and regional (Sigatoka Valley) archaeological records, the sedimentary records of charcoal flux, erosion rates, and vegetation change are quite provocative (Figure 5). Although the nearby Sigatoka Dunes has a well-documented occupation from 2650 cal BP, the hiatus in the record at Caluwe suggests little to no local landscape change for more than seven centuries. The pre-Lapita closed canopy forest within the Caluwe basin seems to have persisted until roughly 1900 cal BP. It is during the post-Lapita period that the surrounding hillslopes were burned and cleared for swidden cultivation ca. 1600–1800 cal BP. Isotopic signatures suggest that fallowing may have been surprisingly short, as indicated by contributions of between 30–40% of C4 plants to the organic carbon pools. This period of intense swidden activity may have been followed by a period of abandonment or reduced use, as indicated by declining charcoal concentrations, depleted carbon isotope ratios, and the slowing of hillslope erosion sufficient to allow for the formation of the Ab1 soil.

A second major phase of swidden establishment and expansion is indicated by the large charcoal peak, accelerated erosion, and enriched carbon isotope ratios that resume around 1450 cal BP. This period of enhanced land-use impacts corresponds in time with the well-dated Fijian Plainware and Navatu occupation of the Sigatoka Dunes site. The beginnings of dune building with terrigenous sediments between these two occupation (ca. 1325 cal BP) suggests that the sediment supply to the Sigatoka River was already increasing at this time. Therefore, the local evidence for expanded swidden cultivation and hillslope erosion in the Caluwe basin may have been mirrored throughout the Sigatoka Valley.

The vegetation communities contributing to soil carbon pools seems to undergo a state transformation at 1000 cal BP with collapse of mixed C3 and C4 communities into the more or less modern *talasiga* dominated landscape, with more than 60% of organic carbon coming from C4 plants. This state transformation is not accompanied by increasing charcoal fluxes, but rather by steady, moderately high charcoal levels (45–50 mg/g). However, between 1300–1100 cal BP, there is evidence for high ($\sim$60 mg/g) charcoal levels that might indicate enhanced burning in mixed fuel, short-fallow swiddens that precipitated the state transformation to degraded *talasiga* conditions. The Vuda phase settlement at Batiri was established within a Caluwe Valley landscape that has already been converted to *talasiga* on the surrounding hillslopes.

In relationship to Fijian culture history, it is important to note that there is no evidence for Lapita-era impacts on the Caluwe watershed, perhaps corroborating the inference that Lapita people were predominantly reliant upon marine foraging throughout their occupation of coastal zones. The records from Caluwe certainly do not indicate that archaeologists should always expect a strong colonization signal in paleofire or vegetation records, as these impacts are likely to vary based on the subsistence activities of the colonists and the nature of the natural resources available to them.

The onset of swidden activity between 1600–1800 cal BP suggests that horticultural land-use in the Caluwe Valley did not occur until after the Lapita era. The period of punctuated swidden use followed by abandonment (or at least a change in agricultural use) is consistent with an argument first made by Spriggs (1997:97–98) that swidden impacts may have been intense and localized but time-transgressive, thus enabling relatively small populations to relocate when swidden returns began to decline. If true, this would suggest that populations in the area were relatively small and that sufficient land was available for horticulturalists to respond to declining returns by moving without risk of conflict with other people.

In the wake of the second major episode of swidden cultivation between 1450–1300 cal BP, such movement may have been less of an option. This period of burning and enhanced erosion coincides with local occupation of the Sigatoka delta but also overlaps a period of rapid local cultural change that may include the immigration of people from outside the Sigatoka region. At some sites there is evidence for an emphasis on defense via the use of remote peaks and steep cliffs for residence, although regional populations were still probably relatively small (Field 2004). The second major period of fortified village establishment occurred within the last 1000 years, the period after the collapse of hillslope vegetation into degraded *talasiga* conditions in the Caluwe basin.

Conclusions

It is important to note that the Caluwe record represents one, relatively small (< 6.5 km^2) watershed in the Sigatoka region and may not be representative of the swidden and land-use history of the region. Indeed, our spatially explicit sampling strategy presupposes that spatial heterogeneity and time-transgressive changes in land-use may have occurred, thus necessitating such a sampling strategy. Nonetheless, the record from Caluwe aligns with the regional archaeological record in a way that suggests some relationships between swidden intensification, population size, conflict, and socio-political complexity. First, even though swidden cultivation is relatively low-investment and the Caluwe Valley is relatively close to areas of known Lapita habitation, inland agriculture seems to have been a less desirable economic strategy so long as marine and littoral resources were abundant and human population sizes were small.

Second, initial swidden cultivation may have commenced with relatively short fallow cycles in which C4 grasses were a significant minority of the biomass burned and cleared for cultivation. This may have been due to the differential costs of the "slash" in "slash-and-burn" cultivation for populations with stone technologies that favored the reuse of early successional swidden patches after they had been established. The period of abandonment after the initial phase of swidden cultivation may indicate that some patches required greater investment to establish as swidden field systems than others and that movement was preferable when swidden returns declined, so long as relocation was possible due to low overall population densities.

Third, sustained swidden cultivation coincides with local occupation of and abrupt cultural change at Sigatoka Dunes, as well as regional evidence for resource stress (Burley 2005; Burley and Edinborough 2014; Visser 1994) and a preoccupation with maintenance of land tenure in the form of fortified villages (Field 2004). Although overall population levels were still probably relatively low, these indicators suggest that residential mobility without intercommunity conflict was no longer a viable response to declining horticultural yields. Intensification of production, including fallow intensification, may have been a response to these changing socio-environmental conditions. Within four centuries, shortened fallow cycles drove the collapse of hillslope landscapes into degraded *talasiga* conditions that persist to the present day.

Finally, it is in the context of degraded landscapes of the last millennium that evidence for socio-political inequality is most robust, in the context of further population growth and intercommunity conflict in the last 500–700 years. This pattern generally conforms to the scenario described by Kirch (1994, 2010), in which landscape degradation from swidden intensification drives cycles of interpolity conflict and socio-political complexity. At Caluwe, however, the evidence for landscape degradation precedes increased evidence for inequality by centuries, suggesting that although swidden intensification and landscape degradation create important historical contingencies for the emergence of complexity, either the temporal lag spans many generations or other factors are also at play.

Our case study suggests that anthropogenic burning and landscape transformation are complicated and contingent processes. Swidden fallowing appears to be impacted by both the costs of establishing new swidden fields and the availability of low-investment/high value horticultural niches elsewhere.

Swidden intensification seems to both respond to changes in the social landscape and alter the conditions under which socio-political changes occur. The research strategy employed here, using terrestrial sedimentary and soil records of biomass burning, post-fire erosion, and vegetation change from small alluvial basins holds great promise for disentangling the spatially heterogeneous and time transgressive nature of anthropogenic transformation and landscape degradation.

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