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Abstract

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Talāsiga Lands in Fiji: Their Potential Expansion through Modern Farming Activities[1]

R. J. Morrison[2,3]

Abstract: *Talāsiga* is a term frequently used in the literature to describe Fijian landscapes with a distinct pattern of plants and soils. The specific meaning in Fijian is unclear and there are varying interpretations of the term in the literature, although authors agree that such areas are indicative of low soil fertility. This paper examines the early literature on *talāsiga*, and attempts to reconcile the differences in use. The possible processes of development of such conditions from forest are discussed and data are presented from recent field studies on the progress from forest to grassland evolution in a 30-year time frame at Seaqaqa, Vanua Levu. The evidence points to the likely change over substantial areas from forest to highly degraded soils and associated grass/fern/shrub vegetation within a very short (<50 years) time frame. Such changes will have dramatic impacts on farmers using such lands.

Keywords: soil, low fertility, vegetation change, processes, organic carbon, land management

TALĀSIGA IS A FIJIAN TERM used to describe landscapes on several islands dominated by a distinct group of plants that are indicative of very low fertility soils. This vegetation assemblage is dominated by grasses, ferns, and trees that are able to survive in difficult growing conditions. Twyford and Wright (1965) wrote that "from the point of view of the Fijian farmer interested mainly in raising subsistence crops, *talāsiga* land is an agricultural desert, worthless to man and beast alike." *Talāsiga* areas are found on the leeward (northwestern) sides of the main islands of Viti Levu and Vanua Levu and on several smaller islands, e.g., Lakeba, Vanuabalavu (Latham 1983).The etymology of the term *talāsiga* is uncertain (Paul Geraghty, personal communication, 2017). The most common English translation is "sun-baked" or "sun-burnt," where the "siga" means sun, but the "talā" (with a long second "a") part is less clear. The situation is complicated by the use of the term *dravuisiga*, which some people (e.g., Twyford and Wright 1965) consider describes a less degraded environment where some subsistence crops will grow, while others consider it to be a dialectal variant of *talāsiga* (Geraghty, personal communication, 2017). The first written occurrence of *talāsiga* is in the Fijian dictionary by Hazelwood (revised edition with Calvert, 1872). It is not found in the first Fijian dictionary (unpublished) compiled in the 1830s by Cargill and other missionaries. This may be related to the fact that they lived in Rewa/Viwa and parts of Lau with limited *talāsiga* areas. Surprisingly the term *talāsiga* is not found in Seemann's *Flora Vitiensis* (1865–72), although several plants common to such areas are listed, e.g., *Miscanthus floridulus* (silvergrass, Fijian *gasau*), *Pteridium aquilinum* var. *esculentum* (bracken, Fijian *koukou* or *qato*), *Dicranopteris linearis* (fern, Fijian *koukouyalewa* or *qato mai*). The

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nonuse of *talāsiga* in *Flora Vitiensis* is even more surprising, as Seemann comments in a report to the Royal Geographical Society (Seemann, 1862, p. 53) on the "fine grassy country, here and there dotted with screw-pines (*Pandanus tectorius*)" that is found on the northern shores of Viti Levu and Vanua Levu. *Talāsiga* appears quite regularly in the literature and various dictionaries after 1900 (e.g., Guppy 1906; Mead 1928; Neyret 1935; Greenwood 1943; Cochrane 1969).

Mueller-Dombois and Fosberg (1998), basing some of their commentary on Cochrane (1969) consider that the original use of *talāsiga* (used to designate a very degraded state of plant retrogression) has been extended, post 1950, to cover the entire dry zone of Fiji, i.e., about one third each of Viti Levu and Vanua Levu. They report that early in the nineteenth century, the dry zones of the major islands were still largely covered with native forests. This does not mean that the zones were not affected by fires used by Fijians in shifting cultivation, rather that the extent of forest reduction was limited. The arrival of Europeans, opening of sugarcane plantations, importation of Indian plantation workers, who in turn leased and cleared land for cane fields, and greater exploitation of their village lands by Fijians led to a rapid expansion of the savanna grassland and fern-grass covered areas.

Mueller-Dombois and Fosberg (1998) consider the true *talāsiga* vegetation to be dominated by the ferns *Pteridium aquilinum* var. *esculentum* and *Dicranopteris linearis* with the associated grass often being *Sporobolus indicus* (they consider that in this terrain even *Pennisetum polystachyon* is rarely found as the soils are too impoverished). When the soils are so degraded, there is not enough fuel for significant fires, and sometimes species like *Casuarina equisetifolia*, *Pandanus tectorius*, *Dodonaea viscosa*, and *Aliphitonia zizyphoides* are found.

When the soils become highly degraded and the vegetation cover is poor, soil erosion becomes prevalent especially early in the wet season when heavy rains occur and little new vegetation has developed. As erosion normally removes the upper soil profile materials, the organic matter and associated N, P, S, and bases held there are also lost, further contributing to soil degradation (Morrison 1998).

The development of *talāsiga* conditions has been debated by many of the authors mentioned above. While there is disagreement about the existence of *talāsiga* lands before the arrival of humans (3000–3500 B.P.), there is considerable evidence that the extent of *talāsiga* increased dramatically after human settlement (Hope et al. 2009, Roos et al. 2016). At this time the islands were mainly covered in forest (Hope et al. 2009, Southern 1986), although the forests would not have been uniform because of the lower rainfall in the leeward (northeastern) sides of the islands. Some authors have described the wet zone forest as "primary" rainforest with a dominance of *Callophyllum* spp., *Endospermum macrophyllum*, *Palaquium* spp., *Myristica* spp., *Canarium* spp., *Heritiera ornithiocephata*, *Syzygium* spp., *Agathis macrophylla*, etc. (Ash, 1992; Mueller-Dombois and Fosberg 1998), while the forest on the leeward sides has been described as "secondary" (Twyford and Wright 1965), "intermediate" (Cochrane 1969) or "transitional" (Marika Tuiwawa, personal communication, 2017), grading into "dry" forest in the driest areas (Keppel and Tuiwawa 2007). The leeward forests above the dry forest tend to be dominated by *Alphitonia zizyphoides* (Fijian *doi*), *Syzygium* spp., *Veitchia filifera* (Fijian *cagicake*), *Acacia richii* (Fijian *qumu*), *Myristica* spp. (Fijian *kaudamu*), *Commersonia bartramia* (Fijian *sama*), and *Parinari insularum* (Fijian *sea*). Given the soil parent materials, the prevailing weathering conditions—relatively high temperatures and rainfall, and their age (Twyford and Wright 1965), the soils in the "transition" zones would generally be relatively deep, of limited fertility with mineralogy dominated by low activity clays (kaolinites, halloysites, oxyhydroxides of aluminium and iron) along with quartz sand and silt particles.

PROCESSES OF *TALĀSIGA* DEVELOPMENT

The following discussion of changes following forest disturbance by fire in the transition zone has been developed from materials in Twyford and Wright (1965), Cochrane

(1969), and Latham (1983). The close interaction between soils and plants cannot be overemphasized; plants are one of the factors that influence soil genesis, by determining to a large extent the amount and type of organic materials in the soil. Plants also respond to changes in the soil. True *talāsiga* soils have minimal fertility (in a chemical sense), with low soil organic matter (SOM) and hence low N (often with a high C:N ratio), and very low contents of bases (Ca, Mg, K, Na), plus minimal nutrients below the topsoil (including a very strong affinity for any added P).

As soils age, the soil plant nutrient status generally declines, especially in the tropics. Thus, by about 15,000 B.P., the majority of soils in the larger Fiji Islands (apart from those like Taveuni with recent volcanism) would have been of an age where only plants that could efficiently use the reduced nutrient supply would continue to flourish. In other words, vegetation change under such conditions would always favor plants able to tolerate a reduced nutrient supply. As noted by Milne (1937, reported in Twyford and Wright 1965) the situation would deteriorate until the nutrient supply is very low, when only plants able to "exist largely on the nutrient supply contained in their own organic residues" would survive. Many tree species can exist under such conditions (Bond 2010) so forest systems can be maintained, but the conditions favor species accumulating resins and waxes, and thus prone to combustion (Orians and Milewski 2007). Under these conditions, soils are also heavily dependent on vegetation to maintain protection from rainfall, strong leaching, and runoff, and hence relative stability in structure and clay minerals under low-base, possibly acidic conditions. The soil organic component is concentrated almost entirely in the topsoil (often quite shallow) and efficiently recycles the plant nutrients in the system. At this point, the soil-plant system is very sensitive to any significant change in conditions.

It is generally agreed that the development of *talāsiga* involves repeated disturbance of the vegetation, most often by fire (either natural or human-induced). Initially on the leeward sides of the large islands, with their strong dry seasons, fires would cause a deterioration in the plant cover (Power et al. 2008), and the soils would have become exposed to dramatically increased extremes in temperature and precipitation. This would lead to erosion at the relatively bare surface in high rainfall, with the loss of the relatively nutrient and SOM-rich surface soil. Further burning will also contribute to loss of SOM (including N and S), and while any P and bases might remain in the ash, being easily mobilized they would only support new growth for a short time before being removed by rainfall-induced leaching and runoff. Ulery et al. (1993) found that wood ash contains calcite, with minor amounts of K and Na carbonates; these materials tend to increase soil pH in the near surface materials, but many ash components are very water-soluble and do not persist through a wet period. Demeyer et al. (2001) report that over 80% of wood ash particles are <1 mm in diameter, with high surface areas, facilitating water solution. Calcite, being less soluble, may be retained longer and maintain a higher than original pH for several years. These conditions would also favor rapid microbiological decomposition of SOM in the remaining topsoil, lowering the CEC, reduction in base retention, and contributing to increased leaching, loss of soil structure, and lowering of erosion resistance. There would also be a tendency to form laterite/plinthite type materials with an enhanced capacity to tightly adsorb P. The whole system would then be so degraded that there would be no capacity to support tree growth and only the most tolerant plants could survive. These are the conditions under which *talāsiga* systems evolve.

Humans dramatically changed the landscape (Hope et al. 2009, Southern 1986, Roos et al. 2016). In preparing food gardens they caused deforestation by cutting down trees, burning the trash, and planting introduced food plants. In the shifting cultivation systems used, the food gardens would have remained in use for limited periods (three to four years, unless terraced) before soil fertility declines would lead to abandonment. If the gardens were abandoned relatively quickly (the humans moving to another location to develop a new garden) saplings from the surrounding forests would move into the 'damaged' area, and

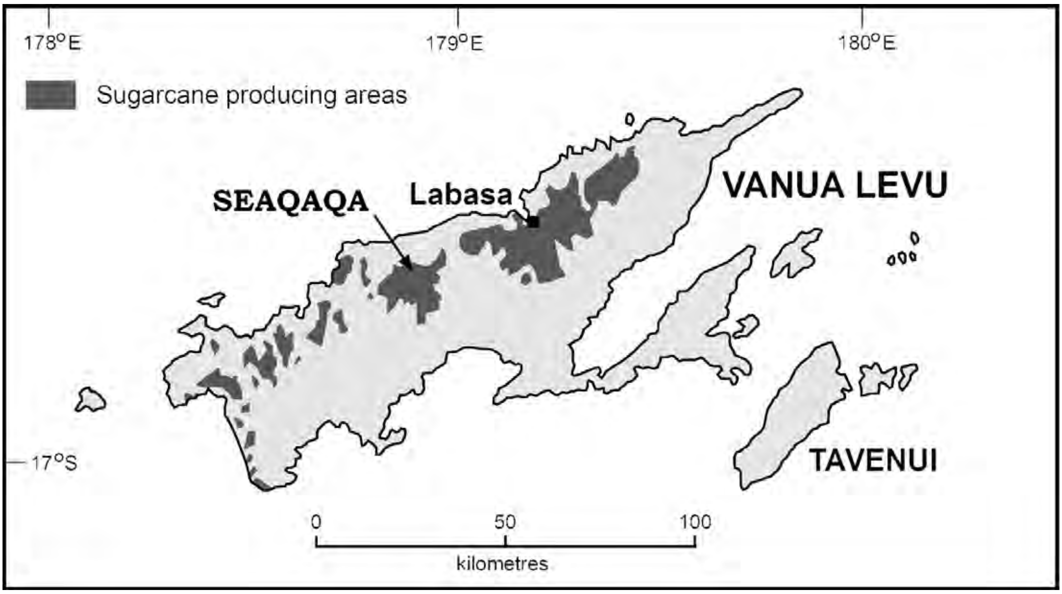

FIGURE 1. Location of Seaqaqa, Vanua Levu, Fiji Islands.

recovery of the forest could occur. If the clearing and burning were repeated a number of times recovery is almost impossible, and in the more degraded areas trees will never grow again. Poor quality grasses, shrubs, and ferns take over. Archaeological and palynological studies confirm this change was very common in the "dry" zones of the larger Fiji islands (Hope et al. 2009, Southern 1986, Roos et al. 2016). Twyford and Wright (1965, p105) also consider that this type of situation also occurred in moderately dry areas and even in some areas with a weak dry season. Latham (1983) reported that similar impacts occurred in Lau where soils initially covered with forest were cleared to provide food for relatively high populations.

Talāsiga areas, based on the literature cited above, have common properties. They are located in the driest areas of Fiji where a strong (≥ 4 months) dry season is a key climate factor. The vegetation is dominated by grasses and ferns with infrequent trees and shrubs. The soils often display a sharp color change on moving from the A (dark gray or brown) to B (red/reddish brown) horizons, frequently showing clear evidence of erosion, with upper layers having higher bulk density than deeper layers. Mottling, originally from weathered C horizons, occurs in many profiles. They have lower SOM than equivalent forest soils with a wider C:N ratio. CECs are generally low, with very low contents of exchangeable bases, while pHs are generally acidic to neutral. They are best displayed on stable landscapes where excessive leaching has occurred, producing a highly oxidized soil material capable of fixing large quantities of P, but they also occur on many steep slopes.

This leads to a key question: Are these conditions of *talāsiga* evolution being created by modern farming activities in parts of Fiji? This project considered this question for the Seaqaqa area of northwest Vanua Levu (Figure 1), using data collected during studies on the long-term impact of introducing sugarcane cultivation. Here three sites were studied for 30 years, with one remaining in native forest vegetation, one being relatively well managed as a sugarcane farm and one being poorly managed.

MATERIALS AND METHODS

The methods used in this study have been reported in Morrison and Masilaca (1988) and Morrison and Gawander (2016) and so only a

TABLE 1

Site and Soil Details

Site	Location	Soil[*]	Site Features	Comments
SQ6	16°32′ 49″ S179°01′ 04″ E	Typic Haplustox, clayey, oxidic, isohyperthermic	Gentle sloping 2° slightly convex SSW-facing 100 m long slope; site in middle third of slope;Elevation 144 m	'Secondary' forest of *Alphitonia zizyphoides*, *Syzygium* spp., *Vietchia filifera*, *Commersonia bartramia*, *Parinari insularum*. Understorey mainly of tree seedlings
SQ5	16°32′ 47″ S179°01′ 04″ E	Typic Haplustox, clayey, oxidic, isohyperthermic	Slightly convex, 4–6°, SW-facing 100 m long slope; site in middle third of slopeElevation 148 m	Forested area similar to SQ6 prior to clearing and planting
SQ4	16°32′ 46″ S179°01′ 05″ E	Typic Haplustox, clayey, oxidic, isohyperthermic	Convex 4–8° NE facing 80 m long slope; site in middle third of slope;Elevation 138 m	Forested area similar to SQ6 prior to clearing and planting

[*] Soil Survey Staff (1999, 2014).

summary is provided here. Three adjacent fields located on rolling terrain were studied; the soils at each site were from the same series and all were under forest cover in the late 1970s (Table 1) when the study began. Two sites (SQ4, SQ5) were converted into typical Fiji sugarcane farms, while the third (SQ6) remained under forest for the study period. Management of the two farmed sites varied considerably with SQ4 operations controlled by a single farmer from the time of land clearance until he retired in 2008. This grower managed the farm well in comparison with other growers in the same area (planting along the contour, trash retention unless burnt accidentally, application of recommended rates of fertilizer, and good crop management and weed control techniques). Sugarcane was harvested manually (green) at SQ4 in almost all years. Site SQ5, however, was not managed well and had to be retired from cane production from 1988 to 1993, and during the 1980s this field received minimal management inputs, suffering from significant erosion as a result of the harvesting being carried out using burning at the end of the crushing season and the soil surface being left bare at the beginning of the wet season. Planting of cane is normally in October–February, with harvesting in late June to November (the wet season usually begins in November in this area).

Prior to vegetation removal and land disturbance or planting of sugarcane, a survey of the area was completed determining soil homogeneity, and a detailed study area of approximately 0.2–0.3 ha was selected. Site details are given in Table 1. Soil pits were dug adjacent to each site, profiles described, and soil samples were collected and analysed and classified (Morrison et al. 1987, Soil Survey Staff 1999, 2014). Subsequently, soil samples were collected from the farmed sites using a bucket auger from three depths (0–15, 30–40, and 70–80 cm) using V transects across the area. Samples (a minimum of 12 for each composite) from two transects were combined and a 1-kg composite subsample for each depth was sent to the laboratory for analysis. The samples were air-dried and ground to pass through a 2-mm sieve (250 µm for carbon and nitrogen analyses). The analytical data reported represent the average of duplicate analyses of each composite. The SQ6 unfarmed site was resampled in a similar way in 2005 and 2009, but the 2009 samples were damaged in transit and subsequently not analyzed. The 2005 data are used to show the lack of change there.

The soil samples were analysed using standard procedures; $\mathrm{pH_{H2O}}$ and $\mathrm{pH_{KCl,1M}}$ were determined using a soil/solution ratio of 1:2.5 after 1 hr of equilibration. Organic C was determined by the Walkley and Black method (Lee et al. 1982). Ion exchange properties were measured by the methods of Blakemore et al. (1981). Total N was determined by the Kjeldahl procedure; water retention against 1500 kPa suction was measured on air-dried samples as described by Gangaiya et al. (1982). Bulk density was determined using a core method (Blake and Hartge 1986). Statistical analysis of the data obtained was carried out using a SPSS Version 13 software package to examine relationships between the various soil parameters.

Vegetation changes during the study period were noted with SQ6 showing little change. Sugarcane yield data were provided by the Fiji Sugar Corporation. Vegetation changes were noted; all plants were identified by staff of the South Pacific Regional Herbarium, University of the South Pacific, Suva.

RESULTS

Analytical data on the soils are presented in Tables 2 through 4. Table 2 shows that for the undisturbed forested site SQ6, minimal change occurred between 1978 and 2005. For the farmed sites (SQ4 and SQ5, Tables 3 and 4), substantial changes occurred after forest clearing and sugarcane planting, especially in the topsoils and upper subsoils, with minimal change in the deeper subsoil (70–80 cm). The data are considered in terms of the topsoils, then the 30–40 cm layers, and then for the 70–80 cm layers. Patterns and trends for various soil parameters (pH, organic C% [OC], total nitrogen % (TN), cation exchange capacity (CEC), 1500 kPa water retention, bulk density and exchangeable (Ca + Mg) over time since land clearing are reported.

Topsoil Samples

pH — The pH_{H2O} values of the topsoil samples generally decreased (from 5.5 to 4.8 for SQ4, 5.7 to 4.6 for SQ5) with increasing period of cultivation. The pH_{KCl} also declined slightly and generally remained in the range 4.8–4.2 over the duration of the study period (375 months). No significant correlations were found for the pH data. The decrease in pH with increasing period of cultivation may be attributed to the effect of various changes—the combination of the decrease in organic matter content, addition of N fertilizers, and removal of bases (Ca, Mg, K) in harvested cane. Such acidification of sugarcane growing soils is common in Fiji (Marlow and Shannon (2013).

Organic carbon and total nitrogen — At both SQ4 and SQ5 sites, there was a marked decrease in the OC content of topsoils within the first 24 months of cultivation (Figure 2). Following the initial decline, the OC content generally stabilized at about 60% of its original value, although some variations did occur; no significant correlations with time were determined. The decline in organic matter content of the soils may be attributed to the substantial mixing with subsoil materials (especially during land clearing) and aeration of soils enhancing mineralization of labile organic matter, plus removal of topsoil during harvesting. Similar changes in OC content of soils have been reported by many previous investigators under conventional tillage systems (Franco et al. 2015). As expected, a close relationship between OC and TN levels in soil, and a significant correlation ($r = 0.63$, $p < 0.05$) was found for all soils. Topsoil TN fell from about 0.46% to about 0.2% after 18 months for both sites, and thereafter remained relatively constant.

Cation exchange capacity — Topsoil CEC values varied over the study period in the range 8–19 cmol/kg. Initially there was a decrease with time after cultivation in line with falls in organic matter. The values then increased and decreased over time (Tables 3 and 4), but showed few significant correlations with other soil parameters.

Bulk density — Bulk density was only examined for the first half of the study. Values generally increased with time, as would be expected as the land preparation and cultivation activities led to a mixing of topsoil and subsoil material, a breakdown in soil structure and compaction, all of which would tend to increase bulk density. The removal of topsoil during harvesting would also have contributed to the increased bulk density. At SQ5, there was a marked increase in bulk density during

TABLE 2

Soil Data for SQ6

Site	Depth (cm)	Date	Time (months)	pH H2O	pH KCl	Org C%	Total N %	P retn %	BD g/cc	15 Bar Water%	CEC/pH7 cmol/kg	Exch Ca cmol/kg	Exch Mg cmol/kg	Exch K cmol/kg	Exch Na cmol/kg	Exch Ca+Mg cmol/kg
SQ 6	0–15	Mar-78	0	5.40	4.50	4.07	0.38	77	1.03	14.50	17.30	8.90	1.80	0.15	0.45	10.70
		Apr-05	325	5.50	4.72	4.58	nd	nd	nd	nd	17.75	11.10	0.78	0.16	1.56	11.88
	30–40	Mar-78	0	5.20	4.90	1.97	0.14	71	1.06	17.70	11.50	1.80	0.25	<0.10	0.30	2.05
		Apr-05	325	5.34	4.80	3.07	nd	nd	nd	nd	13.53	1.41	0.28	0.06	0.59	1.69
	70–80	Mar-78	0	5.30	5.70	0.65	0.04	72	1.13	15.40	2.40	0.50	0.20	<0.10	0.40	0.70
		Apr-05	325	5.38	5.55	0.79	nd	nd	nd	nd	11.91	0.99	0.04	0.03	0.50	1.03

TABLE 3

Soil Data for SQ4

Site	Depth (cm)	Date	Time (months)	pH H2O	pH KCl	Org C%	Total N %	P retn %	BD g/cc	1500 kPa Water%	CEC/pH7 cmol/kg	Exch Ca cmol/kg	Exch Mg cmol/kg	Exch K cmol/kg	Exch Na cmol/kg	Exch Ca+Mg cmol/kg
SQ 4	0–15	Mar-78	0	5.50	4.70	5.59	0.46	67	0.89	14.6	19.00	3.10	1.10	0.20	0.50	4.40
		Feb-80	23	5.00	4.40	4.15	0.28	67	1.08	15.5	13.70	2.30	0.20	<0.1	0.30	2.50
		Dec-81	45	4.90	4.50	4.32	0.28	63	1.10	16.4	21.90	2.10	0.30	0.21	0.50	2.40
		Dec-83	69	4.80	5.60	4.06	0.22	70	1.09	13.6	14.60	1.10	0.14	0.14	0.12	1.24
		Mar-92	168	5.20	4.50	3.14	0.24	68	1.15	14.0	17.30	0.49	0.79	0.17	0.18	1.28
		Sep-93	186	4.80	4.50	2.20	0.22	65	nd	nd	19.20	0.64	0.29	<0.1	0.03	0.93
		Apr-97	229	4.40	4.50	3.56	0.22	59	nd	24.7	19.60	0.82	0.10	0.08	0.12	0.92
		Apr-02	289	4.75	4.33	4.30	0.22	65	nd	nd	19.08	0.77	0.11	0.06	0.43	0.88
		Apr-05	325	5.65	5.36	2.92	0.21	62	nd	nd	16.68	1.40	0.10	0.04	1.18	1.50
		Jun-09	375	4.85	4.34	3.82	0.25	64	nd	nd	9.39	0.11	0.08	0.06	0.03	0.18
	30–40	Apr-78	0	5.70	5.30	1.91	0.15	70	1.07	17.7	7.50	0.50	0.20	<0.1	0.40	1.30
		Dec-83	69	5.80	4.80	2.22	0.12	73	nd	14.0	9.70	0.56	0.07	0.04	0.06	0.63
		Mar-92	168	5.30	5.10	1.28	0.07	82	nd	15.3	11.70	0.34	0.60	0.16	0.20	0.94
		Sep-93	186	4.90	4.90	1.74	nd	75	nd	nd	12.00	0.27	0.11	<0.1	0.03	0.38
		Apr-97	229	4.40	4.60	2.38	0.12	62	nd	21.0	15.20	0.34	0.06	0.04	0.04	0.40
		Apr-02	289	4.58	4.51	2.10	nd	72	nd	nd	8.32	0.64	0.06	0.05	0.41	0.70
		Apr-05	325	5.47	5.05	2.16	nd	57	nd	nd	15.59	1.40	0.15	0.06	0.87	1.55
		Jun-09	375	4.87	4.56	2.99	0.19	70	nd	nd	8.45	0.78	0.14	0.08	0.12	0.92
	70–80	Apr-78	0	5.50	5.70	0.67	0.06	74	1.13	15.5	5.50	0.50	0.20	<0.1	0.40	0.70
		Dec-83	69	5.90	5.60	0.90	0.08	82	nd	13.6	6.00	0.28	0.02	0.02	0.10	0.30
		Mar-92	168	5.90	6.00	0.77	0.05	61	nd	14.8	5.10	0.09	0.17	0.13	0.18	0.26
		Sep-93	186	5.00	5.70	0.81	0.06	67	nd	nd	5.10	<0.1	<0.1	<0.1	<0.1	<0.2
		Apr-97	229	5.10	5.30	0.89	0.03	96	nd	18.6	10.60	0.16	0.04	0.08	0.05	0.20
		Apr-02	289	5.02	5.33	1.40	nd	73	nd	nd	6.94	0.37	0.05	0.05	0.36	0.42
		Apr-05	325	6.05	5.92	0.86	nd	42	nd	nd	7.21	0.37	0.04	0.03	0.63	0.41
		Jun-09	375	5.22	5.03	1.16	0.07	79	nd	nd	4.12	0.06	0.03	0.04	0.03	0.09

TABLE 4

Soil Data for SQ5

Site	Depth (cm)	Date	Time (months)	pH H2O	pH KCl	Org C%	Total N %	P retn %	BD Mg/m3	1500 kPa Water%	CEC/pH7 cmol/kg	Exch Ca cmol/kg	Exch Mg cmol/kg	Exch K cmol/kg	Exch Na cmol/kg	Exch Ca+Mg cmol/kg
SQ 5	0–15	Mar-78	0	5.70	4.80	4.42	0.46	54	0.90	14.3	16.70	3.48	1.24	0.20	0.36	4.72
		Feb-80	23	5.10	4.50	3.22	0.28	51	1.17	15.0	16.90	3.96	0.44	0.10	0.41	3.39
		Nov-80	32	5.10	4.70	3.18	0.26	48	1.14	14.6	15.30	3.95	0.56	0.18	0.24	3.64
		Dec-81	45	5.20	4.70	3.22	0.28	50	1.13	15.3	15.50	3.08	0.37	0.18	0.22	3.78
		Dec-83	69	5.40	4.80	3.00	0.22	63	1.10	13.0	12.90	3.86	0.18	0.09	0.16	0.97
		Mar-92	168	5.70	5.00	1.68	0.13	64	1.38	16.5	30.10	0.25	0.56	0.16	0.17	0.81
		Sep-93	186	5.00	4.40	2.09	0.15	63	nd	nd	17.10	0.07	0.21	<0.1	0.02	0.28
		Apr-97	229	4.60	4.50	2.57	0.13	59	nd	19.3	17.30	0.31	0.05	0.08	0.05	0.36
		Apr-02	289	5.02	4.62	3.30	0.08	66	nd	nd	9.87	0.94	0.12	0.06	0.35	1.06
		Apr-05	325	4.65	4.44	2.56	0.05	46	nd	nd	15.16	0.86	0.10	0.04	0.85	0.96
		Jun-09	375	5.30	4.63	3.44	0.22	60	nd	nd	8.03	0.44	0.15	0.20	0.05	0.59
	30–40	Mar-78	0	6.00	5.50	1.76	0.11	67	1.09	17.2	6.90	0.71	0.21	<0.1	0.15	0.92
		Dec-83	69	6.10	4.90	1.89	0.12	64	1.14	13.6	7.37	0.38	0.07	0.04	0.10	0.45
		Mar-92	168	5.70	5.40	2.18	0.08	73	nd	16.7	12.30	0.46	0.32	0.14	0.16	0.78
		Sep-93	186	5.00	5.30	1.34	nd	71	nd	nd	3.00	<0.1	0.09	<0.1	0.02	0.10
		Apr-97	229	4.90	5.30	1.24	0.01	68	nd	18.3	14.20	0.19	0.04	0.04	0.05	0.23
		Apr-02	289	5.10	5.04	1.70	nd	72	nd	nd	8.06	0.54	0.07	0.04	0.53	0.61
		Apr-05	325	4.53	4.55	1.35	nd	48	nd	nd	11.71	0.84	0.09	0.03	1.71	0.93
		Jun-09	375	5.21	4.82	2.20	0.14	64	nd	nd	6.05	0.28	0.07	0.08	0.06	0.35
	70–80	Mar-78	0	6.10	5.50	0.87	0.08	77	1.17	15.6	4.80	0.45	0.25	<0.1	0.18	0.70
		Dec-83	69	6.00	5.50	0.92	0.06	72	1.18	14.1	5.52	0.16	0.03	0.03	0.14	0.19
		Mar-92	168	5.80	5.60	0.58	0.04	80	nd	18.0	6.58	0.43	0.31	0.33	0.16	0.74
		Sep-93	186	4.90	5.60	0.81	nd	77	nd	nd	0.50	<0.1	0.07	<0.1	0.02	<0.1
		Apr-97	229	5.10	5.70	0.84	0.01	70	nd	14.6	12.30	0.16	0.04	0.04	0.08	0.20
		Apr-02	289	5.22	5.60	1.20	nd	78	nd	nd	7.00	0.45	0.05	0.05	0.32	0.50
		Apr-05	325	4.88	4.90	1.20	nd	47	nd	nd	6.04	0.23	0.03	0.17	0.62	0.26
		Jun-09	375	5.48	5.30	1.24	0.07	77	nd	nd	3.98	0.16	0.03	0.02	0.04	0.19

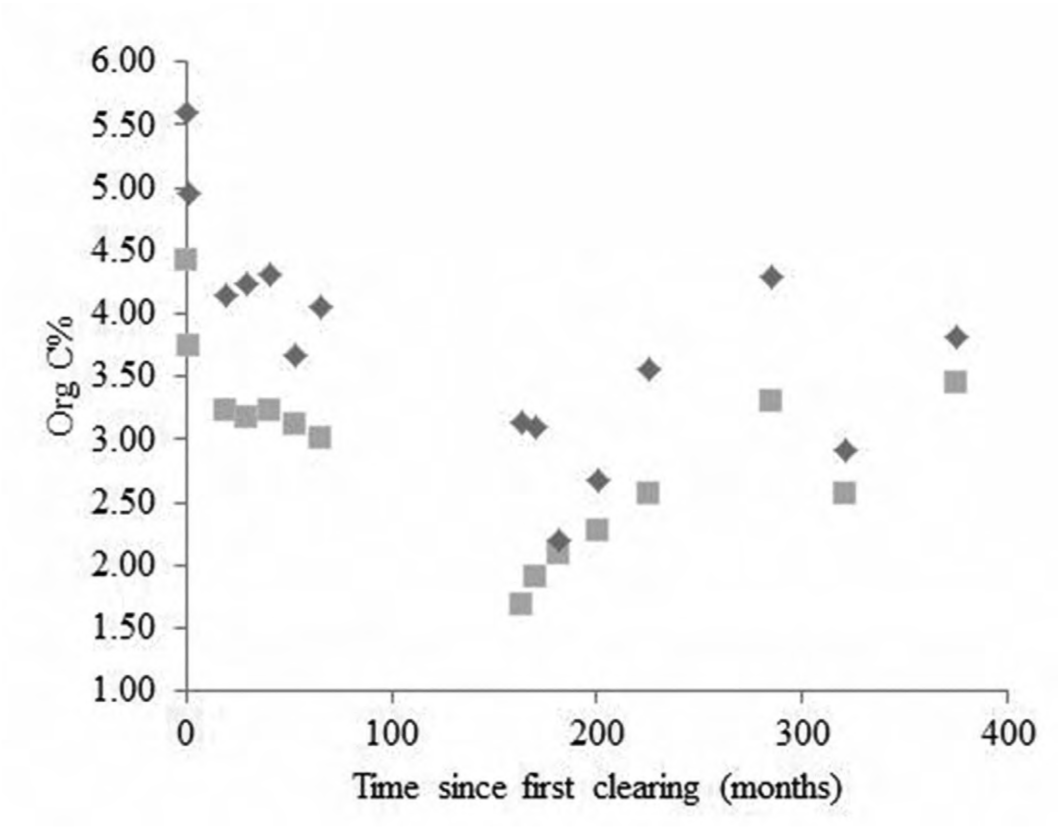

FIGURE 2. Changes in soil organic carbon percentage with time since first clearing of forest for SQ4 (◆) and SQ5 (■).

the first year, and thereafter very little change. No obvious explanation for this difference was found, other than a possible greater depth of mixing of topsoil and subsoil materials during land preparation and cultivation, or a dramatic breakdown in the relatively weak soil structure.

Water retention — The water retention against 1,500 kPa (15 bar) suction was included in the study to monitor the changes in the clay content and surface area of the soils (Gangaiya et al. 1982). The values generally showed a gradual increase with time (Tables 3 and 4), related to structure decline and the breakdown of soil aggregates during land cultivation and harvesting operations producing more small particles increasing the surface area for water retention.

Exchangeable (calcium + magnesium) — Given the decrease in CEC and the increasing acidification of soils, it is not surprising that the exchangeable Ca and Mg values decreased markedly (Figure 3) with increasing period of cultivation. Significant correlations with time were found for both SQ4 and SQ5 ($r = -0.80, p < 0.01$ for both sites). This decrease in the base status of soils may be attributed to a number of factors, including the decrease in the capacity of the soil to retain cations (CEC), the low usage of P containing fertilizers (superphosphate is the main source for added Ca), erosion and crop removal. Morrison and Gawander (2016) estimated that sugarcane crops remove 25–30 kg Ca+Mg/ha/crop, while Ca additions (via fertilizers) at SQ4 and SQ5 were approximately 20–35 kg/ha for the plant crops and 4 kg/ha for

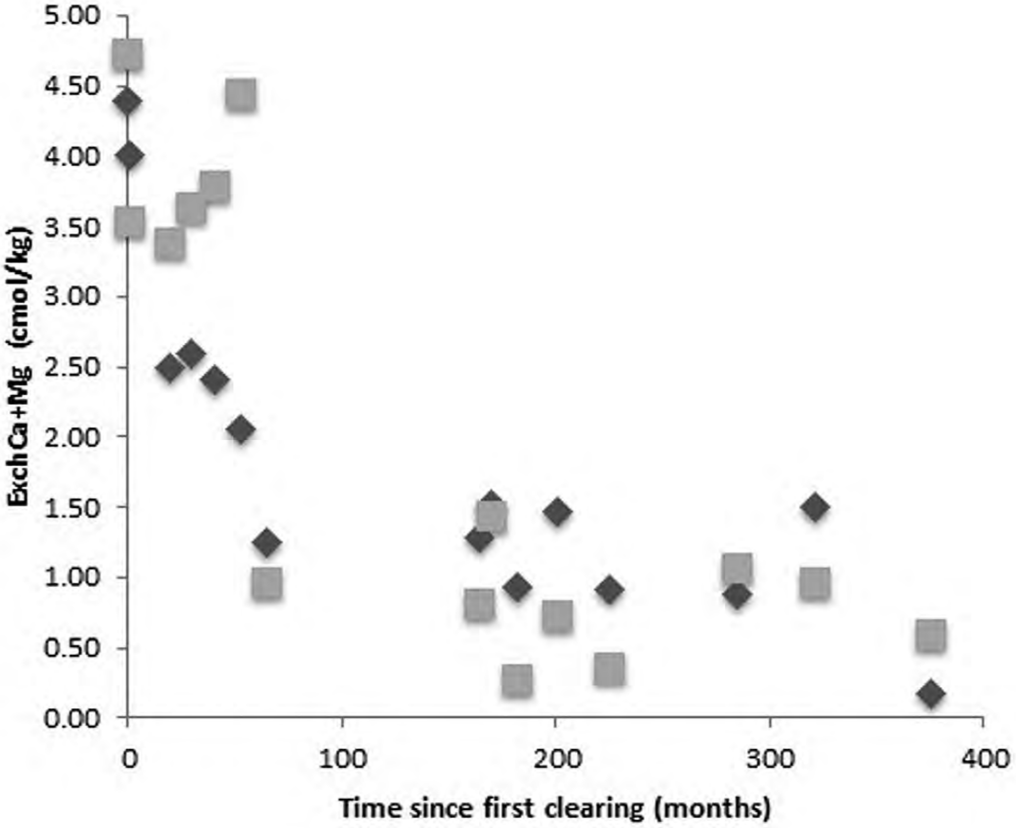

FIGURE 3. Changes in soil ExchCa+Mg contents with time since first clearing of forest for SQ4 (◆) and SQ5 (■).

the ratoon crops (usually no P fertilizers are added to ratoon crops), indicating that in most years more bases were removed in harvesting than were added in fertilizers. Given the initial low base status of soils in this area and the highly weathered nature of the soils (dominated by oxyhydroxide minerals), this loss of Ca and Mg is critical for supporting plant growth for all but the most resilient plants. The ExchCa+Mg values at the end of the study period (<1 cmol/kg) are insufficient to support any efficient crop production.

Subsurface Soil Samples

The results from the analyses of the samples collected at 30–40 and 70–80 cm are shown in Tables 3 and 4. Several points are worthy of discussion.

In the 30–40 cm layers, the most notable changes were a decreasing trend in pH, and an increase in OC with time. This latter increase was significant for SQ4 ($r = 0.78$, $p < 0.05$) but not significant for SQ5. The increased OC was probably due to two factors. First, land preparation for cultivation, that is, tree removal, ripping, and rotovating, would have caused the movement of some topsoil material down in the profile, even to a depth of 30–40 cm. In addition, the roots of sugarcane, which are capable of going down to a depth of 2 m in soils, may have facilitated further accumulation of organic material at depth, either by root development and dieback or even by illuviation. Increasing, but nonsignificant, trends were also observed for CEC and TN.

A similar situation was noted in the 70–80 cm layers, with OC showing a nonsignificant increasing trend with time. The pH_{H20} values showed a weak downward trend, as did exchangeable Ca+Mg. No significant patterns were observed for TN or water retention.

In summary, over the period 1979–2009, SQ5 topsoil showed minimal pH change, a 25% decrease in organic C, a 55% drop on total N, C:N increased from 9.6 to 15.5, CEC dropped by 50%, and the exchangeable Ca +Mg dropped from 4.7 to 0.6 cmol/kg. In the 30–40 cm layer the SOC and total N did not change much from the initial levels, the CEC dropped only marginally but the Ca+Mg dropped by more than 50%. In the 70–80 cm layer, the SOC rose gradually through the study period from 0.80 to 1.24%, the total N did not change much, the CEC dropped by about 20%, while the Ca+Mg dropped by about 70% to 0.19 cmol/kg. SQ 4 showed similar changes in both the 30–40 and 70–80 cm layers with the Ca+Mg finishing at very low (<.1 cmol/kg) levels. In the field, it was noted in 2009 that SQ4 had better surface soil structure than SQ5, and SQ5 had some areas showing signs of yellow and black mottling on the surface. This may be due to the SQ4 site being less damaged during harvesting (no burning) and lower erosion losses at that site.

Sugarcane Production Data and Vegetation Changes

As noted above, SQ5 was poorly managed and the results can be seen in yields (Table 5), with yields dropping to uneconomic levels within 10 years, while SQ4 remained productive for > 25 years. SQ5 was "retired" from cane production in 1988 and over the following four years was left unattended until a new farmer replanted in late 1992. During the years of nonproduction, the vegetation that took over the SQ5 site was dominated by *Pennisetum polystachyon* and a few small shrub and forest species (Table 6).

TABLE 5

Sugarcane Yields for SQ4 and SQ5, 1978–2009

Site	SQ4		SQ5	
	Yield		Yield	
Year	(Tonnes)	(t/ha)	(Tonnes)	(t/ha)
1980	703	74.8*	416	47*
1981	640	68.1	340	43
1982	575	61.2	395	56
1983	564	60	278	46
1984	550	58.5*	216	34
1985	327	34.9	150	47*
1986	453	44.4	56	14
1987	379	44	52	24
1988	568	61.8*	16	20
1989	480	50	0	0
1990	648	68.2	0	0
1991	577	60.8	0	0
1992	678	71.4	0	0
1993	512	53.9	288	51*
1994	580	61	356	50
1995	551	58	495	56*
1996	580	62.3*	428	49
1997	443	48.1	395	45*
1998	387	43	317	37
1999	485	51.6	466	57*
2000	505	53.2	373	46
2001	460	50	192	37*
2002	524	63.9*	192	27
2003	379	46.2	84	21
2004	369	45	107	19
2005	457	55.7	132	28
2006	419	58.1	168	29
2007	361	55.5	0	0
2008	252	38.8	0	0
2009	283	43.5	0	0
Mean	**490**	**52.9**	**197**	**29**

* = plant crop.

SQ4 remained productive until 2008 when the farmer retired. After his retirement, the cane continued to grow into 2009, but was gradually being overgrown with weeds, including *Pennisetum polystachyon* and *Mikania micrantha*. Even after replanting in 1992, the SQ5 site remained precarious from a sugarcane production perspective, with yields declining almost linearly ($R^2 = –0.77$, $p < 0.01$) from 1993 to 2006 when the site was permanently retired, despite five replantings in 13 years (the average replanting time in this

TABLE 6

Vegetation Changes Observed for SQ4, SQ5, and SQ6, 1978–2009

Year	SQ6	SQ5	SQ4
1978	Transitional Forest (see Table 1)	Transitional Forest (see Table 1) cleared and sugarcane planted	Transitional Forest (see Table 1) cleared and sugarcane planted
2002	Transitional Forest (see Table 1)	Dominant *Pennisetum polystachyon* with isolated *Passiflora foetida* and *Acacia* sp saplings	Sugarcane with minimal weeds
2009	Transitional Forest (see Table 1)	*Pennisetum polystachyon* with some *Dicranopteris linearis* and *Sporobolus indicus??*	Sugarcane (unmanaged) with some *Pennisetum polystachyon* and few *Mikania miscantha*

area is every 5–6 years). By 2009, SQ5 was again dominated by *Pennisetum polystachyon* but, in addition, *Dicranoptersis linearis* ferns were also becoming common, i.e., the site was showing the sort of vegetation that is found in true *talāsiga* sites. As shown in Figure 4, this combination can often lead to extensive areas of bare soil surface prone to erosion in wet weather.

DISCUSSION

The most important changes in the sugarcane soils were the decrease in surface soil organic

FIGURE 4. Site SQ5 in 2009 showing limited surface cover with remnant (post-natural-fire) *Pennisetum polystachyon* and *Dicranopteris* ferns (Site SQ6 is in the background).

FIGURE 5. Seaqaqa area showing sugarcane fields interspersed in transitional forest.

C due to ripping and rotovating (mixing of profile to a depth of 30–35 cm) and an additional decline due to organic matter decomposition. There was a corresponding increase in organic C in the 30–40 cm layer in both soils (as a result of soil mixing) in the first year. There were associated changes (decrease in 0–15 layer, increase in 30–40 cm layer) in the CEC as the SOM is a major contributor to the CEC in these low-activity clay soils. The initial rapid changes were followed by more gradual changes as the systems adjusted to new management conditions. As noted above, SQ5 was poorly managed and the results can be seen in yields (Table 5), with yields dropping to uneconomic levels within 10 years, while SQ4 remained productive for > 25 years. SQ5 was "retired" from cane production in 1988 and over the following four years was left unattended until a new farmer replanted in late 1992. During the years of nonproduction, the vegetation that took over the SQ5 site was dominated by *Pennisetum polystachyon* (Mission grass, introduced into Fiji in 1920 [Mueller-Dombois and Fosberg 1998]), an aggressive invasive species, and a few small shrub and forest species (Table 6).

Site SQ5 would appear to have reached the *dravuisiga* stage of degradation described by Twyford and Wright (1965). *Pennisetum polystachyon* has as one of its main attributes the ability to invade and dominate tropical areas after fire; it is drought-tolerant and tolerates both acid and alkaline conditions (FAO 2017). It is fairly shade tolerant, does not suffer from any major diseases and has no serious pests. It is very prone to fire and with the surface coverage shown in Figure 4 it is likely rapid degradation through erosion and fires will accelerate; loss of nutrients and SOM will continue with the full *talāsiga* situation soon to be achieved.

Site SQ4 is also distinctly degraded, but has maintained a cover of sugarcane resulting from better farm management and limited use of fire in harvesting. This site is probably also at the *dravuisiga* stage, but because of better vegetation coverage may take longer to degrade to full *talāsiga* conditions.

One feature of the *talāsiga* soils highlighted by Twyford and Wright (1965), but not seen at SQ 4 and 5, is the color change from the A to B horizons; in this situation this is a result of the original soil showing minimal color changes through the profile (the original colors were dominated by dark red [2.5 YR 3/6] and red [2.5 YR 4/6]). In addition, the SOC in the surface layer, although declining following cultivation is still, after 30 years, around 3%, while most true *talāsiga* soils have SOC contents of about 1% or less. Maintaining higher levels of SOC is important in providing some nutrient fertility to the soils and enabling more demanding plants to grow (Quinton et al. 2010). The retention of higher SOC contents in the SQ4 and SQ5 soils maybe an unexpected outcome from the initial land preparation procedures. As noted in the Methods, land preparation involved the removal of trees, including uprooting, ripping, and rotovating the soils to depths of about 35–40 cm. In doing this, organic matter gets mixed in the soil profile to such a depth, and this "buried" organic matter is protected from erosion by the soil above. So while surface erosion may occur removing the SOC in that layer, a substantial amount of SOC remains in the profile in what is the new (post-erosion) surface.

The changes described above all fit well with the process model for *talāsiga* development discussed earlier. Continuing disturbance of the soil vegetation system, whether by fire (natural or man-made), ploughing, or crop harvesting will lead to a rapid degradation of these highly weathered soils that only have a minimal capacity to retain essential nutrients in the topsoil.

Thus it can be seen that human activity has changed this forest soil into a highly degraded grassland soil showing features approaching those of the *talāsiga* soils in just 30 years. This is a major concern as much of the Seaqaqa area is being changed in a similar way with substantial transitional forest areas having been cleared for sugarcane cultivation (Figure 5). Degradation is more rapid in poorly managed farms. Given that some 5,500 ha of sugarcane have been planted in this area, serious degradation of a considerable area may occur within one lifetime, leaving a substantial area unsuitable for any other land use. Every effort should be made to encourage farmers to adopt good soil management practices to slow down or minimize the loss of productive land.

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