

Carbon status and structural stability of soils from differing land use systems in the Kingdom of Tonga

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Abstract

Maintenance of soil carbon stocks is vital for the environment at large and for maintenance of soil chemical, physical and biological fertility. Tonga represents a country in agricultural transition from subsistence to commercial production and whilst this is good for the national economy the impact on soil resources is less clear. The major cropped soils, fallow vegetation types and forest systems of Tonga were identified in each island group and samples of representative soils (0.15 m depth) from each land use unit were taken. Total carbon (C_T) and $\delta^{13}C$ were measured and labile carbon (C_L) determined by oxidation with 333 mM $KMnO_4$. These data were used to determine the carbon management index (CMI) and the proportion of carbon from C4 species in the C_T pool. Relative to primary forest, the soil C_T and C_L generally declined with changes in vegetation and more intense mechanical tillage. The contribution of C4 plants to soil C increased with intensity of mechanical tillage and the prevalence of C4 guinea grass (*Panicum maximum* Jacquin) fallow. The changes in soil C were reflected in the CMI, and C_L was a more sensitive indicator of change than C_T . These data indicates that all land use systems have experienced a large net loss of soil C relative to the forest systems. Soil mean weight diameter (MWD) decreased significantly with increased intensity of mechanical tillage and to a lesser extent with the intensity and length of cropping. The relationship between soil MWD and soil C was similar with soil C_T and C_L . Grass fallow was as effective as permanent vegetation systems in improving soil MWD and lowering the micro-aggregate (<125 μm) fraction.

Keywords: Soil organic matter, pacific islands, fallow, cultivation, soil aggregates

Introduction

Maintenance of soil carbon stocks is vital for the environment at large and for maintenance of soil chemical, physical and biological fertility. The Kingdom of Tonga is undergoing rapid changes in agricultural practices and attention is needed to understand the impact on soil carbon.

Tonga consists of 171 islands scattered over a total area of 700 000 km². The total land area of these islands is about 747 km², with 48 of the islands inhabited. The soils of Tonga have been described in detailed soil surveys (Wilde & Hewitt, 1983; Cowie *et al.*, 1991), and the main islands consist mainly of low and raised coral limestone overlaid by

a mantle of two different layers of fine-grained andesitic volcanic ash, estimated to be 20 000 and 5000 yr old, and derived from the western volcanic islands. Differences between soils in the Tongatapu, Ha'apai and Vava'u groups are mainly due to variations in the thickness of the young volcanic ash, the coarseness of which decreases from the western to the eastern side of the islands.

Generally, these clay loam soils have high to very high clay content dominated by halloysite (>95%). The Fe-oxide minerals (mainly haematite, but also less weathered forms such as ferrihydrite and goethite) gives the rusty colour, soil retention of P and SO_4^{2-} and aid in soil aggregation. Differences in structure and properties of these ash soils are closely related to the nature and content of the 1–5% Fe-oxide minerals (Trangmar, 1992). These *Typic Argiudoll* and *Hapludoll*, very fine, halloysitic, isohyperthermic, clay loam

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soils (>60%) are friable, well structured, well drained and with moderate plant available soil moisture. Tonga has a subtropical maritime climate, which is mild to warm, humid and moderately wet throughout the year. From the Tongatapu Islands in the south (ca. 21.30°S) to the Niuaus (ca. 16.00°S) in the north, the mean annual minimum temperature increases from 20.7 to 23.7 °C, the mean annual maximum temperature increases from 27.1 to 29.8 °C, and the mean annual rainfall increases from 1719 to 2356 mm.

Agriculture in Tonga is basically shifting cultivation, although with various modified forms evolving on different islands, and with different combinations of crops and fallow species. The traditional cropping system involves partial clearance of secondary fallow vegetation, followed by mixed and relay cropping for about 3–5 yr before being allowed to revert back to bush fallow.

By contrast the production of squash for export uses mechanical tillage, fertilisers and pesticides on a monocrop base of a few high yielding varieties. Since 1987, the islands of Tongatapu, Vava'u and 'Eua have been the main producers of squash, which are mostly exported to Japan. Squash production resulted in a threefold increase in the cropped area in Tongatapu, Vava'u and 'Eua Islands. This resulted in increased use of mechanical tillage, fertilisers and pesticides for squash production and for the production of other crops such as vegetables and watermelon for the local market.

The high clay content of the soil makes the structure very fragile when wet and prone to damage when tilled. As the soil structure is degraded, in combination with increased mixing of topsoil with subsoil and exposure to air, there is increased mineralisation of soil organic matter. This is exacerbated by the current trend of increasing the length of the cropping phase with very short fallow periods, to almost continuous cropping.

Using data from plant residues labelled with ^{14}C and ^{13}C Blair *et al.* (2005) postulated that in some soils large macroaggregates form around smaller macroaggregates and that the rate of breakdown of the plant residues has a major effect on the longevity and integrity of the macroaggregates.

Whitbread *et al.* (2000) used the soil C pool fractionation methods with KMnO_4 oxidation (Blair *et al.*, 1995) and found that the soil macroaggregate fraction contained much more soil C_T (total C) and C_L (labile C) than the microaggregate fraction. Blair *et al.* (1998) found that the relationship between soil aggregate stability and soil C_L fraction was much stronger than with the soil nonlabile (C_{NL}) or C_T fractions, but especially for soils with clay contents less than 49%. Further, Bell *et al.* (1998) experimenting on Red Ferrosols, found a stronger relationship between the soil micro-aggregate fraction <125 μm , following wetting by simulated rainfall and C oxidised by 33 mM KMnO_4 than with 333 mM KMnO_4 . The objective of this study was to

examine the effects of agricultural practices on soil carbon dynamics and on aggregate stability.

Material and methods

Soil sampling

The sampling of representative soils from each land use unit was undertaken as follows. In each island group, the major cropped soils, major fallow vegetation types and forest systems were identified. The following major land use systems units were identified: primary and secondary forest, shrub vegetation, traditionally cropped forest, permanent crops/vegetation, grass fallow >5 yr, at least 5 yr cropping (mechanized tillage, fertiliser and pesticides) with grass fallow rotation >2 yr, at least 5 yr continuous cropping (mechanized tillage, fertiliser and pesticides) with grass fallow <1 yr. Primary forest was natural lowland rainforest. Secondary forest had coconuts (*Cocos nucifera*) and other fruit trees featuring largely in the vegetation. The permanent vegetation and/or crops were shrub vegetation such as *Leucaena*, *Lantana*, *etc.*, and/or coconuts, annual crops (e.g. yam (*Dioscorea alata* L.) or perennial crops (e.g. vanilla (*Vanilla fragrans*)) crops integrated with a mixture of different tree species.

These units were visited, appraised and the largest uniform site with known land use history was selected to represent a particular land use system. Soil cores of 0.15 m depth were taken at 5- to 10-m intervals on at least two transects across the survey unit. At least 50 soil cores were taken, mixed and a subsample of about 2 kg was placed in a labelled plastic bag. At the laboratory, visible stones, vegetative and organic debris were removed from the soils, before they were air-dried at 40 °C to a constant weight. A subsample for soil particle analysis was gently crushed to pass a 4-mm sieve, and the second subsample for the C and nutrient analysis was milled to pass a 500 μm sieve.

The total number of soil survey units sampled was 50, with 27 samples from Tongatapu Island, 11 from Haápai and 12 from Vavaú.

Determination of total carbon (C_T) and labile carbon (C_L)

The total carbon (C_T) and $\delta^{13}\text{C}$ was determined using a Carlo Erba NA1500 Automatic Nitrogen and Carbon Analyser Mass Spectrometer (ANCA-MS). Soil samples containing ca. 350 μg carbon were weighed into tin capsules and these flash oxidised in an oxygen stream in the ANCA-MS. C4-derived soil C was calculated assuming a $\delta^{13}\text{C}$ of -24.05 for the C3 forest (mean of forest samples) and a $\delta^{13}\text{C}$ value of -12.00 for the C4 guinea grass. Labile carbon (C_L) was determined using the procedure described by Blair *et al.* (1995) which considers that the 333 mM solution of KMnO_4 oxidises

C compounds in the soil in a way similar to that of enzymes produced by soil micro-organisms (Loginow *et al.*, 1987). The carbon management index (CMI) of Blair *et al.* (1995) was calculated.

Wet aggregate stability. Immersion wet sieving was undertaken by placing a 30 g soil sample which had been sieved to <4 mm on the top of a nest of five sieves of 2000, 1000, 500, 250, 125 μm sizes with a diameter of 100 mm. A further 125 μm sieve was used for a lid. The air dry soil was weighed onto the 2000 μm sieve and immersed in distilled water for 30 s, before sieving for 10 min through an amplitude of 17 mm at 34 cycles/min. Following sieving, the sieves were drained and the soil dried at 40 °C for 24 h prior to weighing. Mean weight diameter (MWD) was calculated after Kemper & Rosenau (1986). MWD is the weighted average of soil mass in each aggregate size fraction. It is an index of aggregate size distribution in each treatment. The % of aggregates >250 μm and the % of aggregates <125 μm were also calculated.

Results

Tongatapu

Clearing of forest and cultivation resulted in large declines in soil C_T and C_L on Tongatapu Island (Table 1). Relative to the primary forest, the trend and rate of the decline is related to the length of fallow, the fallow species composition, the intensity of cultivation and the intensity of mechanical tillage. The reduction in soil C_T was 43% for permanent vegetation and/or crops, 50% for grass fallow, 59% for rotation of crops and grass fallow and 66% for the continuous mechanical tillage cropped soil.

The carbon management index calculated from the proportional changes in C_T and the lability with the primary forest as the reference was low ranging from 47 to 23 (Table 1). Mechanical tillage and grass vegetation resulted in a lower CMI. The soil $\delta^{13}\text{C}$ measured for these soils

increased from – 23.19 for the forest to – 17.09 for the repeatedly cropped soil. The calculated soil C contribution from the C-4 grass vegetation ranged from 7% for the primary forest to 73% in the repeatedly cropped soil (Table 1). The high value for the latter practice was mainly due to the annual incorporation of the guinea grass (C4) fallow vegetation prior to cropping.

Wet aggregate stability. The soil MWD for the primary forest, permanent vegetation and grass fallow were comparable at about 2.6 mm (Table 1). Similar values for the particle size fraction <125 μm were also recorded for the above 5 land use systems. The decline in soil MWD relative to the primary forest was 48% for the cropped grass fallow and 72% for the continuously cropped soil. The effects occurred in the soil particle fraction <125 μm where there was a ca. twofold increase for the cropped grass fallow and about a fourfold increase in the continuously cropped soil. The data showed the large differences in soil aggregate stability due to the intensity of mechanical tillage. Therefore, the soil particle fraction <125 μm increased as the macroaggregate fraction disintegrated due to increased mechanical tillage and intensity of cropping.

The MWD for the permaculture was 2.37 mm compared with 0.54 mm for the 20 yr old continuously cropped soil.

Ha'apai

Land clearance and cultivation resulted in large declines in soil C_T and C_L on Ha'apai Island (Table 2). However, the trend and rate of the decline was much less than for 'Eua, which most likely is related to the length of fallow, the fallow species composition, the intensity of cultivation and the intensity of mechanical tillage. The reduction in soil C_T was 24% for permanent vegetation and/or crops, 42% for grass fallow, 38% for cropped grass fallow and 47% for the repeatedly mechanical tillage cropped soil. The reduction in soil C_L was proportionally similar, but with different amounts to soil C_T .

Table 1 Total C (C_T), labile C (C_L), carbon management index (CMI) and % contribution from C-4 plants to soil C from different land use in Tongatapu

Land use system	No. of samples	C_T (mg/g)	C_L (mg/g)	CMI	% Soil C-4 C	MWD (mm)	Fraction <125 μm (%)
Primary forest	2	80	16	100	7	2.65	2.6
Permanent vegetation/crops	8	47	8	47	55	2.48	4.0
Guinea grass fallow	4	41	7	41	58	2.65	2.6
Mechanically cropped and grass fallow	9	34	6	30	64	1.37	5.9
Repeatedly mechanically cropped	4	28	5	25	73	0.77	12.2
Standard deviation		4				0.76	1.2

CMI, carbon management index; MWD, mean weight diameter.

Table 2 Total C (C_T), labile C (C_L), carbon management index (CMI) and % contribution from C-4 plants to soil C from different land use in Ha'apai

Land use system	No. of samples	C_T (mg/g)	C_L (mg/g)	CMI	% Soil C-4 C	MWD (mm)	Fraction <125 μm (%)
Primary forest	2	65	28	100	11	2.44	0.3
Permanent vegetation/crops	2	49	10	83	21	2.38	0.3
Guinea grass fallow	1	38	7	53	20	2.06	1.3
Traditionally cropped shrub/grass fallow	4	40	8	56	61	1.81	1.3
Repeatedly mechanically cropped	2	35	6	46	56	0.81	2.0
Standard deviation		6				0.25	1.0

CMI, carbon management index; MWD, mean weight diameter.

The carbon management index for land use systems of Ha'apai ranged from 83 to 46 (Table 2). The impact of mechanical tillage and grass vegetation resulted in a much lower soil C. The soil $\delta^{13}\text{C}$ measured for these soils increased from -22.77 for the forest to -17.35 for the repeatedly cropped soil. The calculated soil C contribution from the C-4 grass vegetation ranged from 11% for the primary forest to 61% in the traditionally cropped shrub/grass fallow. The high value for the latter practice was mainly due to the annual incorporation of the grass fallow vegetation prior to cropping.

Wet aggregate stability. The soil MWD for the primary forest and permanent vegetation were comparable at about 2.4 mm, and grass fallow and the cropped grass fallow soils at about 1.9 mm (Table 2). The soil MWD declined by 21% for the cropped grass fallow and 67% for the continuously cropped soil.

The particle size fraction <125 μm was comparably low for the primary forest and permanent vegetation soils and was high for the grass fallow, cropped grass fallow and continuously cropped soils (Table 2). The data showed the huge reduction in soil aggregate stability due to the intensity of mechanical tillage. Therefore, the soil particle fraction <125 μm increased as the macroaggregate fraction

disintegrated due to increased mechanical tillage and intensity of cropping.

Vava'u

Land clearance and cultivation resulted in large declines in soil C_T and C_L on Vava'u Island (Table 3). Relative to the primary forest soil, the soil C_T declined by 34% for permanent vegetation or crops, 45% for grass fallow, 50% for cropped grass fallow and 57% for the repeatedly mechanically tillage cropped soil.

The carbon management index for soils of Vava'u ranged from 55 to 26 (Table 3). The impact of mechanical tillage and grass vegetation resulted in a much lower soil C. The soil $\delta^{13}\text{C}$ measured for these soils increased from -24.05 for the forest to -15.18 for the repeatedly cropped soil. The calculated soil C contribution from the C-4 grass vegetation ranged from 0% for the primary forest to 74% in the repeatedly cropped soil. The high value for the latter practice was mainly due to the annual incorporation of the grass fallow vegetation prior to cropping.

Wet aggregate stability. The soil MWD for the primary forest was the greatest at 3.16 mm, and declined by 26% for the permanent vegetation and grass fallow, and 43% for

Table 3 Total C (C_T), labile C (C_L), carbon management index (CMI) and % contribution from C-4 plants to soil C from different land use in Vava'u

Land use system	No. of samples	C_T (mg/g)	C_L (mg/g)	CMI	% Soil C-4 C	MWD (mm)	Fraction <125 μm (%)
Primary forest	2	81	19	100	0	3.14	0.3
Permanent vegetation/crops	3	54	12	55	37	2.38	1.7
Guinea grass fallow	2	44	7	44	68	2.09	0.9
Cropped shrubs/grass fallow	2	41	8	40	24	1.33	1.4
Repeatedly mechanically cropped	3	35	5	26	74	0.95	8.3
Standard deviation		3				0.19	1.4

CMI, carbon management index; MWD, mean weight diameter.

cropped grass fallow and 70% for the continuously cropped soil (Table 3).

The particle size fraction $<125 \mu\text{m}$ was comparably small for primary forest, permanent vegetation, grass fallow and cropped grass fallow but was large for the continuously cropped soil. The data indicated a large reduction in soil aggregate stability due to the intensity of mechanical tillage. Therefore, the soil particle fraction $<125 \mu\text{m}$ increased as the macroaggregate fraction disintegrated due to increased mechanical tillage and intensity of cropping.

Discussion

This survey has shown that the soil C_T and C_L changed with different land use systems in the islands of Tonga. Relative to primary forest, the soil C_T and C_L generally declined with changes in vegetation and intensity of mechanical tillage.

Donato *et al.* (2012) found that soils of the savannah areas on the Pacific islands of Yap and Palau contained substantially less soil C than mangrove soils. Similar to the present study, Hsieh (1996) found soil C_L declined by 66% after 20 yr of continuous sugar cane production relative to the secondary forest in Belize. In the chromic luvisols in semi-arid northern Tanzania, Solomon *et al.* (2000) showed that soil C was reduced by 56%, when tropical woodland was cleared and cropped. Detwiler (1986) found that soil organic matter of primary tropical forest declined by 17–27, 20 and 30% during the cropping phase of the shifting cultivation, pasture and continuous cultivation, respectively. Palm *et al.* (1996) compared results on the decline of soil C after cultivation of tropical forest. The reduction in soil total C ranged from 10–40% for different soil types in different sites and countries. In Nigeria, Juo *et al.* (1996) found that soil C under 15 yr of continuous maize with fertiliser and no-tillage declined by 50% as compared with regrowth bush fallow for 15 yr (soil C = 20 mg/g). The results of regression of 625 paired soils by Mann (1986) showed that the greatest rate of decline of soil C with cropping occurred in the first 20 yr. An initial C effect was present, that is, soils with very low C tend to gain small amounts of C during cultivation, whereas soils high in C lost at least 20% during cultivation.

The large reduction in soil C_T in Tongatapu found in the present study (Table 1) was mainly the result of the high intensity of mechanical tillage. This is associated with the high production of crops for export and food for the higher population density in Tongatapu as compared with the other islands. Continuous mechanical tillage would increase the exposure of soil to air, resulting in higher rates of decomposition of soil organic matter in the higher temperature and rainfall of Vava'u. The trend was also seen with the changes in CMI for Vava'u and Tongatapu. The CMI for Tongatapu decreased from 47 to 25 for repeatedly

cropped system, and for Vava'u, the CMI decreased from 55 to 26. This suggests that the climatic effects of higher temperature and rainfall for Vava'u prevailed and compensated for the more intensive repeatedly cropped system of Tongatapu. Jenkinson & Ayanaba (1977) have showed that decomposition of incorporated ryegrass increased with higher temperature with the rate of ryegrass decomposition four times higher in the tropics (26 °C) than in a temperate climate (9.2 °C).

In this research, the results showed that the contribution of C4 plants to soil C increased with intensity of mechanical tillage and the prevalence of C4 grass fallow. Wiser *et al.* (1999) reported that by area, the vegetation in Tongatapu consisted of 49.4% under mixed vegetation of coconut (*Cocos nucifera* Linn.) and guinea grass (*Panicum maximum* Jacquin), 22.8% under guinea grass vegetation only and 6.4% under coconut with regenerating forest or shrub vegetation. For Vava'u and Ha'apai, the area under guinea or Johnson grass was less than 20%. Therefore, the abundance of C4 grasses and the intensity of mechanical tillage, which incorporates the grass biomass into the soil, increased from Vava'u in the north towards Tongatapu in the south. As a result, the contribution of C4 plants to soil C also increased from Vava'u to Tongatapu. In Belize, Central America, Hsieh (1996) found that the contribution from 20 yr of continuous sugarcane production to soil C-C4 was about 30%.

This survey has shown that in Ha'apai, the traditional cropping of *Leucaena* shrub vegetation or incorporation of 4 yr of a bean/legume rotation can maintain soil C_T and C_L concentrations. In Tongatapu, permaculture (>20 yr) resulted in about twice the concentration of soil C_T and C_L than the areas repeatedly cropped with mechanical tillage (>20 yr). Juo *et al.* (1996) found that soil surface organic C was ca. 20 mg/g after 15 yr of fallow of guinea grass, or *Leucaena*, or natural bush regrowth. The soil C accumulation with the planted fallow of guinea grass or *Leucaena* was comparable to that of natural bush regrowth. They concluded that unless planted fallow provides other significant benefits to the farmers, the fallow by natural bush regrowth is the best option.

This survey of the carbon status of soils of Tonga has shown a general decline in C status with intensity of cropping. Labile C (C_L) was a more sensitive indicator of change than C_T and the CMI was found to be a useful indicator of the C status of the systems. Introduction of reduced tillage practices, legume rotations and mulching, particularly with the large biomass of guinea grass that accumulates in the fallows, are all likely to slow this rate of decline, or even reverse it.

This study, like those of da Silva *et al.* (2013) and Assmann *et al.* (2013), has shown that the CMI is a sensitive indicator of soil C status of agricultural systems.

Table 4 Linear regression relationship between mean weight diameter (MWD) and soil total C (C_T) and labile C (C_L) for the soils of the different Islands in Tonga

Island	MWD = $a + b C_T$			MWD = $a + b C_L$		
	<i>a</i>	<i>b</i>	r^2	<i>a</i>	<i>b</i>	r^2
Tongatapu	-0.74	0.06	0.50**	-0.38	0.27	0.42**
Ha'apai	-1.49	0.08	0.53**	-0.82	0.36	0.62**
Vava'u	-0.64	0.05	0.83**	0.15	0.19	0.78**

MWD, mean weight diameter; ns, non significant. **Significant at $P = 0.01$.

Soil physical fertility

In general, the soil MWD declined with the intensity of mechanical tillage and to a smaller extent, the frequency of cropping. This was manifested in the differences in rate of decline of MWD in the traditionally cropped system as compared with mechanically tilled and cropped system. The MWD of the continuously cropped system for Tongatapu, Ha'apai and Vava'u, where mechanical tillage was practised, was reduced to 60% of the MWD of forest system. The largest reduction in MWD relative to forest system was 72% for the continuously cropped system in Tongatapu. The comparable 70% soil MWD reduction for continuously cropped system in Vava'u is likely due to the impact of the higher rainfall and temperature on Vava'u which compensates for the lower cropping intensity, relative to Tongatapu. However, the higher content of the soil micro-aggregate particle fraction ($<125 \mu\text{m}$) for the continuously cropped system on Tongatapu of about 12% relative to 8% for Vava'u emphasises the larger impact of intensity of mechanical tillage on soil structure. This indicates that the soil micro-aggregate fraction becomes enriched when the macro-aggregate fraction disintegrated with increasing used of especially mechanical cultivation and to a lesser extent the cropping intensity with very little fallow.

Generally, the soil MWD for forest, permanent vegetation and/or crop and grass fallow systems were comparable ranging from 2.01 to 3.16 mm. The soil MWD for the forest system was consistently the highest and the grass fallow was at the lower end. Conversely, the soil micro-aggregate fraction ($<125 \mu\text{m}$) also increased in the cropped systems as compared with fallow, permanent and forest system. Therefore, given enough time, the grass fallow was as effective as the forest system in increasing the aggregation of the soil. This is a great advantage due to the natural regrowth of Guinea and Johnson grass within a year, whereas shrub vegetation and forest required at least 15 yr in the cropping system of Tonga to effectively re-establish. It is generally observed that as the intensity of mechanical tillage increases, the natural regrowth

vegetation shifts from Guinea grass dominant to Johnson grass dominant.

There was a linear relationship between soil MWD and soil C_T and C_L and this varied for different islands of Tonga (Table 4). Perusal of the mean data presented in Tables 1–3 suggest the attainment of a threshold level of C but when individual site data within each island is used, as in Table 4, this is not so. The correlation coefficient was highest for Vava'u and decreased towards Tongatapu. The linear regression correlation coefficients between the MWD and the soil C_T or C_L were generally similar. The similarity of the relationships between the three islands suggests that if mineralogy affects the relationship then it is of minor consequence. In contrast, Blair *et al.* (1998) report the linear regression correlation coefficient between MWDs of 20 soils ($<50\%$ clay) was 24–32% higher with the soil C_L relative to the soil C_T .

Intensification of cultivation in these fragile soils has led to a severe decline in soil C stocks which in turn has reduced soil physical fertility. The abundance of Guinea grass which grows in the fallow periods offers scope to utilise this resource as mulch material for subsequent plantings which would likely reverse or halt the current degradation processes.

Concurrent measurements of soil C and soil structural stability are valuable in understanding the broad consequences of soil degradation as a result of developments in cropping systems.

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