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Stable isotopes for characterisation of trends in soil carbon following deforestation and land use change in the highlands of Madagascar

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Abstract

The impacts of human land use in the highlands of Madagascar are often equated with land degradation and decreasing soil fertility. The practice most often focused on is deforestation through slash-and-burn cultivation (*tavy*), and shifting cultivators are often portrayed as being ignorant, poverty-stricken peasants felling trees for fields and food. However, there is uncertainty whether soil degradation is related to recent tavy or earlier forest clearance, and whether some highland areas were ever forested. In this paper we use stable isotopes ($\delta^{13}C$) and diffuse reflectance spectroscopy (DRS) to study the impacts of deforestation and various other land use changes on ecosystem properties, soil organic carbon (SOC) dynamics and soil quality (fertility) in the highlands of Madagascar. Land cover transitions (between C_3 and C_4 systems) are defined and quantified in the study area. Historical land use had greater effect on soil organic carbon concentrations than current land use, with cultivated areas previously under C_3 and C_4 systems having 37.3 and 14.8 g SOC kg^{-1}, respectively. Grasslands previously under C_3 had approximately 124% more SOC than grasslands previously under C_4, while SOC concentrations were 65.3 and 54.9 g C kg^{-1} under natural forest and in mixed fallow systems, respectively. A soil fertility index developed for the study area based on diagnostic soil spectra was compared with findings related to SOC dynamics and land use change.

Keywords: Soil organic carbon; Stable isotopes; Soil fertility; Deforestation; Land use change; Diffuse reflectance spectroscopy; Madagascar

1. Introduction

Deforestation and cultivation of previous forest soils represents a significant challenge for quality soil management in the highlands of Madagascar, especially since this region is dominated by inherently nutrient poor soil types (i.e. Oxisols) and is experiencing decreasing availability of land due to population growth during the last 50 years. There are, however, major uncertainties related to historical deforestation and land use change due to limited historical data coupled with a simplistic view that shifting cultivation (*tavy*) is the main reason for the loss of forest cover, soil fertility decline and environmental degradation. Jarosz (1993) suggested that the most significant period of deforestation was between 1896 and 1925, triggered by French colonial economic policies, including timber production (extraction of precious woods) and the introduction of coffee cash cropping. The current grasslands of the highlands, which cover vast areas, are often presented as

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having been covered by natural forest in some distant past. The view that these forests were cleared following human settlement on the island is widespread and largely adopted by major international development institutions. However, Grandidier (1905) suggested that the lack of forest in the highlands was natural, a view supported by several other researchers and by more recent studies, including that of Burney (1997) who demonstrated that Madagascar was never totally covered by forest.

The impacts of human land use such as deforestation and cultivation on structural and functional ecosystem properties can be studied using stable isotopes (Boutton et al., 1998; Staddon, 2004). Stable isotopes are isotopes that do not undergo radioactive decay, but their isotopic composition is subject to natural variation due to mass dependent fractionation. Isotopes of the same element take part in the same chemical reactions, but because the atoms of different isotopes are of different sizes and different atomic weights they react at different rates. Physical processes such as evaporation discriminate against heavy isotopes; and enzymatic discrimination and differences in kinetic characteristics and equilibria can result in reaction products that are isotopically heavier or lighter than their precursor materials. This leads to pools with different compartments of an ecosystem where the isotopic composition of the elements is indicative of their history. The applications of stable isotopes in ecosystem studies are diverse, and include studies of (i) element fluxes, (ii) translocation of nutrients within metabolism, (iii) evaluation of matter input into a system and (iv) retrospective analysis of changes within a system. In biological and hydrological studies, stable isotopes of H, C, N, O, S, B and Li are generally of interest.

The naturally occurring $\delta^{13}C$ values for biologically interesting carbon compounds range from roughly 0‰ to −110‰ relative to the Pee Dee Belemnite (PDB) standard. C_3 plants, those using the Calvin–Benson (Calvin and Benson, 1948) photosynthetic pathway, fractionate carbon differently from C_4 plants that use the Hatch–Slack (Hatch and Slack, 1970) pathway. In C_3 plants CO_2 is reduced to a three-carbon compound and they generally exhibit $\delta^{13}C$ values in the range of −33‰ to −22‰ (Deines, 1980), with a mean of −27‰ for woody plants. C_4 plants, however, reduce CO_2 to a four-carbon compound and show $\delta^{13}C$ values ranging from −17‰ to −9‰, with a mean of −14‰ (Boutton et al., 1998). These differences occur because C_3 plants discriminate more heavily against the heavier isotope than C_4 plants (O'Leary, 1981).

Most tropical grasses, including maize (*Zea mays*), sorghum (*Sorghum* spp.) and natural savanna grasses have the C_4–C assimilation pathway. The conversion of natural forests and planting or succession of C_4 plants in soils previously supporting C_3 plants can be considered an in situ labeling of newly incorporated organic matter into the soil (Solomon et al., 2002) as the relative proportions of C_3 and C_4 plants change following land cover change. Soil C from the previous plant community will decay out of the SOC pool and be replaced by C derived from the new plant community and the isotopic discrepancy created by land cover change will therefore persist for some time (Boutton et al., 1998). The time that it takes for C from the old plant community to be depleted from the SOC pool is determined by, and can be used as a direct measure of, organic matter (SOM) turnover rate (Cerri et al., 1985; Bernoux et al., 1998).

The main objective of this study was to assess topsoil SOC trends and turnover as affected by current and historical land use (land cover transitions) using stable C isotopes ($\delta^{13}C$). A secondary objective was to relate the development of a soil fertility index (SFI) (Vågen, 2004; Vågen et al., in press) based on soil visual-near-infrared (Vis-NIR) spectroscopy, which is a non-destructive, rapid and cost-effective soil analysis method, to trends in SOC and $\delta^{13}C$.

2. Materials and methods

The study was conducted in the eastern highlands of Madagascar, in the province of Fianarantsoa, close to the city of Ambositra (20°31′42″ S and 47°14′48″ E) (Fig. 1).

2.1. Soil analysis

Soil samples were collected along a 26 km transect covering a wide range of transition stages and land use types in the study area, using a stratified random sampling design based on land use. Field surveys and interpretations of satellite images dating between 1972 and 2001 were used in land use mapping and selection of sampling areas. Sampling plots were randomly selected within land use types. Composites of 10 soil samples were collected from each plot of approximately 30 by 30 m, corresponding with Landsat ETM + image pixels. Sampling was conducted in August/October 2002 and November/December 2003. Soil samples within each plot were randomly selected and mixed to yield one composite sample per plot. A total of 200 soil samples were collected, and a subset of 101 soil samples was selected for stable carbon isotope analyses.

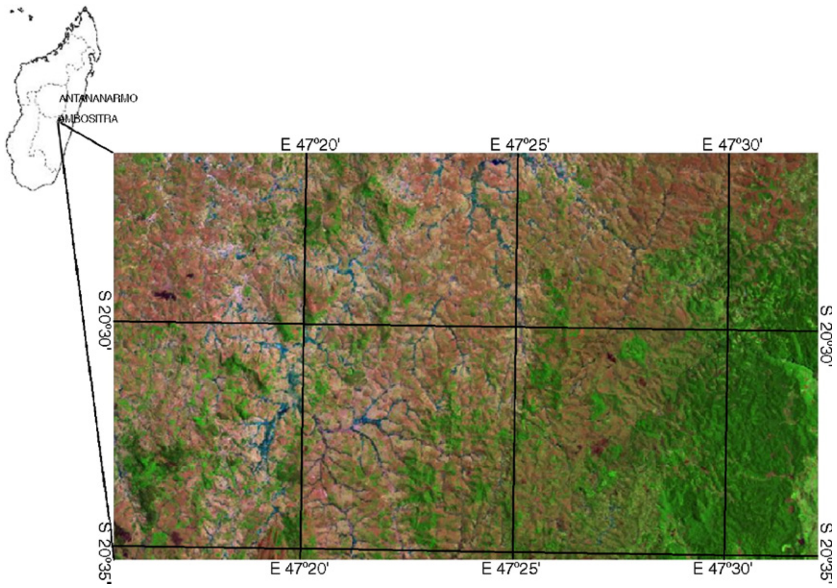

Fig. 1. Map of study area showing location relative to map of Madagascar.

Carbon (SOC) and nitrogen (TN) contents were analyzed by dry combustion in a C/H/N/S-analyzer. Natural ^{13}C abundance was determined with an elemental analyzer coupled with an isotope ratio mass spectrometer. Stable ^{13}C isotope abundance is commonly expressed as $\delta^{13}C$ in per mil (‰), as the relative ratio of the heavy isotope ^{13}C to the light isotope ^{12}C in a sample, relative to the Vienna-Pee Dee Belemnite (PDB) limestone standard;

$$\delta^{13}C(‰) = \left[\frac{\left(\frac{^{13}C}{^{12}C}\right)_{sample} - \left(\frac{^{13}C}{^{12}C}\right)_{std}}{\left(\frac{^{13}C}{^{12}C}\right)_{std}}\right]1000$$

Soil visible near-infrared reflectance was measured relative to a white reference using a FieldSpec FR spectroradiometer (Analytical Spectral Devices Inc., Boulder, Colorado) at wavelengths from 0.35 to 2.5 μm with a spectral sampling interval of 1 nm, as described by Shepherd and Walsh (2002) and Vågen et al. (in press), but using the optical setup described in Shepherd et al. (2003).

2.2. Land cover transitions

We studied SOC and $\delta^{13}C$ dynamics under land cover conversions from former C_3 to current C_4 and former C_4 to current C_3 as per the following definitions:

- Current vegetation:
  - Presence of woody vegetation (C_3);
  - Woody and graminoid vegetation (mixed);
  - Presence of graminoid vegetation (C_4);
- Former vegetation:
  - $\delta^{13}C < 19.5‰$ (C_3);
  - $\delta^{13}C \geq 19.5‰$ (C_4).

The following transitions were studied in a set of chronosequences covering natural forest, recent conversions, mixed fallow, cropland, eucalyptus (planted) and savanna grasslands;

- Former C_3 to current C_4;
- Former C_3 to current mixed;
- Former C_4 to current mixed;
- Former C_4 to current C_3.

Time since conversion for the various soil sampling points was established through analysis of land cover change using a time-series of satellite imagery (Landsat MSS, TM and ETM+) covering the period from 1972 to 2001 (Vågen, 2004) combined with interviews with farmers and the analysis of aerial photographs (from 1957 and 1991).

2.3. Soil fertility index (SFI)

The Expectation Maximization (EM) algorithm (Dempster et al., 1977), as implemented in the MIM (Edwards, 2000) graphical modeling software package, was applied to develop ordinal soil condition classes (i.e. poor, average and good) for soils of the study area

based on ten commonly used agronomic indicators of soil fertility (Vågen et al., in press). The indicators used were pH, SOC, TN, available P, exchangeable Ca, Mg and K, cation exchange capacity (CEC), and silt and clay contents.

A soil fertility index was then developed from diffuse reflectance soil spectra (DRS), which have earlier been successfully used to predict important soil chemical (e.g. SOC and TN) and physical (e.g. clay, silt and bulk density) properties and provide integrated measurements of soil condition (Hummel et al., 2001; Shepherd and Walsh, 2002; Vågen et al., unpublished). Details on the SFI approach are presented in Vågen et al. (in press).

2.4. Statistical analysis

Differences in δ^{13}C, SOC and SFI between land use types and various times after clearing of natural forest were analyzed using multiple comparison tests (Venables and Ripley, 2003), summarized in tables and visualized using box-plots and simple point and bar graphs with standard error estimates included. The relationship between SOC and SFI was analyzed using a non-linear asymptotic regression model of the general form (Pinheiro and Bates, 2000);

$$y(x) = \theta_1 + (\theta_2 - \theta_1)\exp[-\exp(\theta_3)x],$$

where $\theta_{(1,2,3)}$ are model parameters and x is SOC.

The turnover rate of SOM was estimated through a “dose” function where each dose corresponds to a given probability that all C from the previous land cover type has decayed out of the SOC pool (i.e. $\delta^{13}C < 19.5$ or $\delta^{13}C > 19.5$, depending on past land cover). This is also commonly known as LD50 (details in Venables and Ripley, 2003).

A classification model using decision trees (CART) was developed in Matlab version 6.5 (Mathworks, Inc.) to identify Vis-NIR spectral regions that were diagnostic of soil condition (SFI) (details in Vågen et al., in press). The bands identified were used as predictors in a logistic regression model, with soil condition as the dependent variable.

3. Results and discussion

3.1. Land use dynamics

The deforestation pattern in the study area develops like a mosaic as local shifting cultivators clear patches of forest for tavy. Certain grasslands near present forest margins were reported by local experts and farmers to be old, while others were cleared less than 20 years ago. The cultivation pattern was complex as different farmers cultivated their land for different periods of time (normally 2 to 4 years) after clearing, mainly depending on availability of land and on-site soil fertility. The duration (normally 1 to 4 years) and number of mixed-fallow cycles varied for the same reasons. However, the general pattern was an abandonment of cultivation after approximately 10 to 12 years when farmers reported that soils became nutrient-depleted to a point where yields diminished (after the second or third cultivation cycle). In valley bottoms, forests were generally converted to paddy, with continuous cultivation for more than 50 years in well managed areas. However, the clearing of the forest was also reported by farmers to lead to less availability of water in some areas, forcing them to switch to dryland crops (often vegetables) and later to abandon cultivation in these areas altogether. Grasslands were periodically burnt (every 1 to 3 years) and in some areas grazing pressure was high. In western parts of the study area (most populated) marginal grasslands were also put into production, leading to severe soil degradation (erosion, wastelands).

For the specific sampling points reported here, the most important land use conversions during the 29 year period included in the satellite image analysis were grassland savanna to dryland cultivation (*tanety*), conversion of rainforest to tavy, mixed fallow and permanent cultivation, and planting of Eucalyptus in former natural forest and grassland areas.

3.2. SOC dynamics as related to current and past land use

The isotopic composition of SOC (δ^{13}C) was lower in current forest and mixed fallow systems than under other land use types, as expected given the dominance of woody vegetation in these areas (Fig. 2). Cultivated areas included both recent conversions and old cultivated fields, and the range in δ^{13}C was therefore high (Fig. 2). Grouping the data according to the definitions of current land use given earlier (i.e. C_3, mixed and C_4 vegetation) showed that conversions from former C_4 systems had significantly lower SOC contents than from former C_3 systems, with cultivated areas previously under C_3 systems having an average topsoil organic carbon concentration of 37.3 g C kg^{-1} compared with 14.8 g C^{-1} under C_4 systems. This suggests that historical land use was more important in explaining the variation and trends in SOC than current land use (Fig. 3). Soils under former C_4

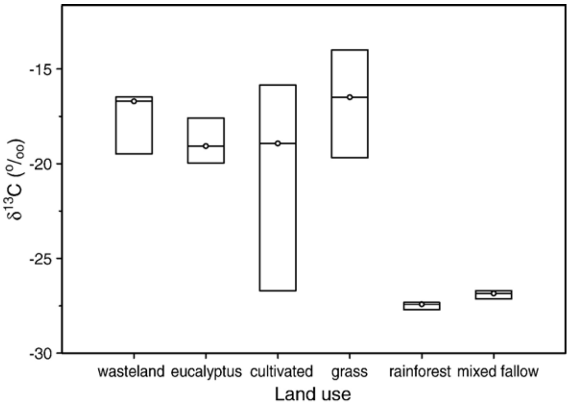

Fig. 2. The isotopic composition of SOC (δ^{13}C) under current land use practices. Points show median values and box edges are fourths.

systems (i.e. old grasslands or long-term cultivation) also showed a narrow range in SOC as compared to soils under current C_4 systems (Fig. 3). Former C_3 systems converted to cultivation showed significantly higher SOC contents than when former C_4 systems (grasslands) were cultivated (Table 1). Concentrations of SOC stabilized at about 15 g C kg (SE=2.3) under long-term cultivation, while old grasslands stabilized at approximately 20 g C kg (SE=1.7). Trends in SOC were mirrored by the δ^{13}C isotopic composition for the various land cover conversion types (Fig. 4), showing the importance of δ^{13}C as an indicator of change in soil quality.

The estimated time at which there was a 50% probability that initial C_3–C had been depleted from current SOC (LD50) was determined to be 26 (SE=6.1), 27 (SE=5.6) and 20 (SE=6.7) years for cultivated, mixed and grassland systems, respectively.

Table 1
SOC under current land use, as affected by past (historic) land use

Current land use	SOC (g C kg^{-1}) Former land use		
	C_3	C_4	
Cultivated	37.3^{a}	14.8^{a}	†
Eucalyptus	20.4^{a}	21.5^{a}	
Grassland	53.2^{a,b}	23.8^{b}	†
Wasteland*	17.5^{a}	12.6^{a}	
Mixed fallow	54.9^{a,b}		
Natural forest	65.3^{b}		

Different letters indicate significant difference between rows;
†Significant difference between columns;
*Only one replicate in former C_3.

3.3. Soil fertility index as related to SOC dynamics

Ten diagnostic wavelengths were initially identified as being optimal splitters on soil condition (details in Vågen et al., in press). These were reduced to 5 final bands (570, 1410, 1940, 2040 and 2390 nm) based on significance tests in the logistic regression model (p=0.0030). The spectrally based SFI showed an increase with increasing SOC in the range from less than 5 to about 60 g C kg^{-1}, after which it asymptotically approached saturation (Fig. 5). The saturation at approximately 60 to 65 g C kg^{-1} corresponded with the average SOC content of natural forest soils (Table 1), indicating that the SFI describes changes in soil quality well after conversion from natural forest. This was confirmed for other soil properties also, including total nitrogen, available phosphorus and cation exchange capacity (not reported here).

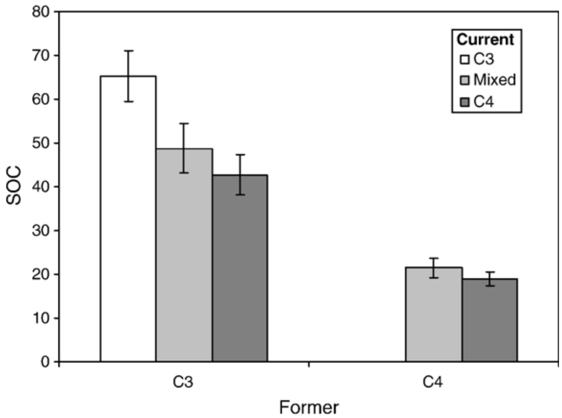

Fig. 3. SOC (g kg^{-1}) as affected by former and current land use. Error bars show standard error of means.

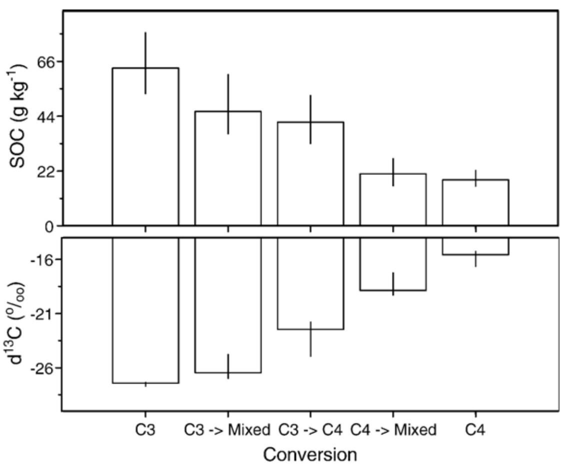

Fig. 4. SOC (g kg^{-1}) and δ^{13}C (‰) as affected by land use conversions. Stick plot shows 95% confidence limits.

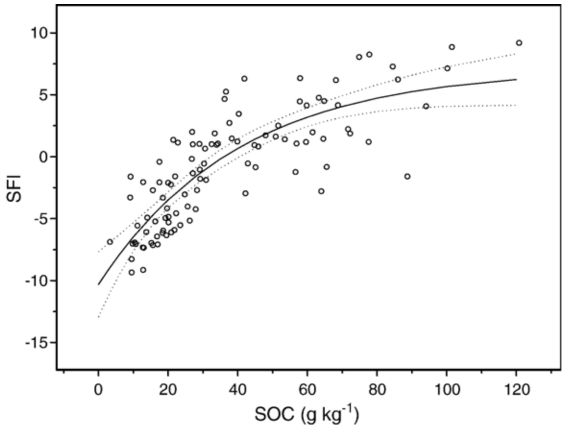

Fig. 5. Change in SFI at increasing SOC contents showing non-linear asymptotic regression curve with 95% confidence limits (SFI = 7.11 + (−10.31 − 7.11)exp[−exp(−3.69)SOC]).

Trends in the SFI following land use conversions confirmed the importance of past (historic) land use for soil fertility decline, with C_3 systems and conversions from C_3 to mixed systems having significantly higher SFI values than conversions from C_4 and stable C_4 systems (i.e. long term cultivation or grasslands) (Fig. 6). The index reflected the decline in SOC when former C_4 systems were cultivated as well as low SOC concentrations in wasteland areas (Table 2). It is also interesting to note the low SFI in *Eucalyptus*. The decline in soil fertility was gradual during the first 5–10 years after clearing, but declined significantly in the long-term and closely mirrored the isotopic composition of SOC in the study area (Fig. 7). Thus SFI was a good indicator of soil degradation and fertility decline in the study area, and reflected trends in both SOC and

Table 2
SFI under current land use, as affected by past (historic) land use

Current land use	SFI former land use		
	C_3	C_4	
Cultivated	1.1^{a}	-5.1^{a}	†
Eucalyptus	-5.5^{b}	-4.4^{a}	
Grassland	$-0.7^{a,b}$	-3.3^{a}	†
Wasteland*	$-2.1^{a,b,c}$	-6.2^{a}	
Mixed fallow	$2.2^{a,c}$		
Natural forest	4.8^{c}		

Different letters indicate significant difference between rows.
†Significant difference between columns.
*Only one replicate in former C_3.

$\delta^{13}C$ following conversion of natural forest and land use change.

4. Conclusions

This study has demonstrated the use of stable C isotopes to better understand historic land use change and its implications for current SOC and soil fertility status and trends in the highlands of Madagascar. Former land use was found to be a more important determinant of SOC dynamics in previous tropical forest areas and old grasslands than current land use.

A soil fertility index developed based on Vis-NIR reflectance spectroscopy was compared to the dynamics of SOC and $\delta^{13}C$ following deforestation (conversion) and land use change. The SFI functioned as a direct indicator of soil fertility decline in the study area and reflected SOC and $\delta^{13}C$ dynamics well. Soil fertility decline was most severe when former C_4 (i.e. grassland) systems were cultivated (SFI = −5.1) and in areas

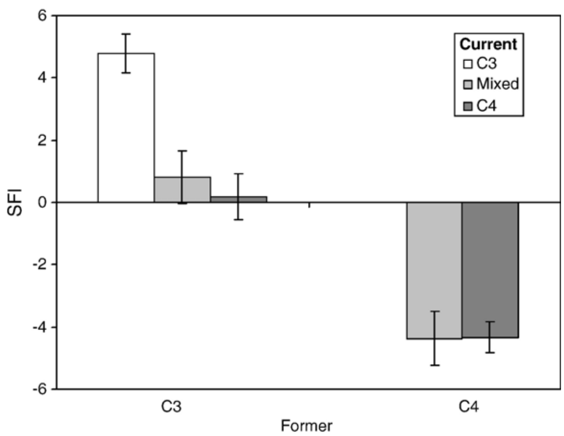

Fig. 6. SFI as affected by past and current land use. Error bars show standard error of means.

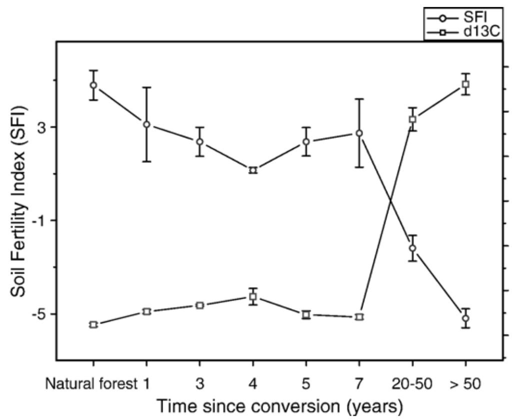

Fig. 7. Change in soil fertility index (SFI) and isotopic composition ($\delta^{13}C$) with time since conversion (TSC), showing means and standard errors.

showing visible signs of degradation (wastelands) (SFI = −6.2). Natural forest soils had the highest SFI values (mean = 4.8). The potential of the SFI for rapid and cost-effective characterisation of soil fertility decline (or degradation) is therefore highly encouraging.

These findings also show that (traditional) tavy may not lead to significant reductions in soil fertility when soils are left to regenerate after 3 to 4 years of cultivation, but confirms the general trend of soil fertility decline in the highlands of Madagascar due to shorter fallow periods and an expansion of the area under intensive cultivation. Cultivation of old grassland areas due to scarcity of agricultural land leads to rapid soil fertility decline and severe soil degradation. The findings of this study also support other findings by Shepherd and Walsh (2002), Shepherd et al. (2003), Vågen (2004) and Vågen et al. (in press).

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