Effects of cropping systems and manuring on soil microbial and C status of a vertisol in Ethiopia

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Anbausysteme und Gründüngung beeinflussen mikrobielle Parameter und den Kohlenstoffstatus von Vertisol in Äthiopien

1. Introduction

Vertisol is one of the dominant soil orders in Ethiopia. However, its productivity is severely limited by its poor physical qualities (drainage and workability) and low N and P status. Recuperation of soil fertility by the use of chemical inputs (fertiliser, pesticides) is challenged by a low fertiliser efficiency, poor economic structure of Vertisol holders, and preference of crop residues for other uses. Besides, the growing economic and environmental concern about agrochemical inputs has kindled interest in the development of sustainable management systems that rely on soil biological processes (MANDAL et al., 1999). Agroforestry systems are increasingly considered as a form of sustainable land use in tropics for it may provide food, firewood, fodder, and cash benefits without impairing soil fertility (CHINNAMANI, 1993).

However, reports on the effect of alley cropping systems on crop yield and quality of soil are inconsistent (KANG, 1993; PALM, 1995). So far, its success and failure has been investigated only on physically stable soil and mostly with return of prunings into soils. Information on microbial processes and C_{org} status under cool-humid tropical climate and on high activity smectite clay soil is scanty, and none is available for alley cropping systems where prunings are not returned to soil. In the present study we considered the effect of cropping systems and soil treatments on microbial parameters and C_{org} and carbohydrate content of a self-churning Vertisol in cool-humid equatorial Africa.

Zusammenfassung

Der Einfluß von Anbausystemen und Gründüngung (Weizen-Monokultur mit und ohne *Sesbania sesban* im Reihenanbau, sowohl mit als auch ohne einmalige Einbringung von Pflanzenrückständen von Sesbania und Klee) wurde in einem Feldexperiment auf Vertisol in kühl-tropischem Klima (Hochland von Äthiopien) untersucht. Sieben Jahre nach Beginn des Experimentes wurde der Pflughorizont viermal innerhalb einer Vegetationsperiode beprobt und Basalatmung, mikrobielle Biomasse C (C_{mic}) und N (N_{mic}), organischer C (C_{org}), Gesamtkohlehyratgehalte (C_{hy}), pH und Gesamt-N bestimmt.

Streifenanbau von Sesbania führte zu einem Anstieg von C_{org}, C_{mic}, Basalatmung, qCO_2, dem C_{mic}:C_{org}-Verhältnis und Gesamt-N, während unter Monokultur C_{mic}:N_{mic} und das C:N-Verhältnis erhöht waren. Eine einmalige Anwendung von 5 bzw. 10 t ha^{-1} Sesbania-Schnitt bewirkte einen Anstieg von C_{org}, der noch nach 7 Jahren meßbar war. C_{org}-Gehalte von gründgedüngten und Bracheflächen waren höher als die auf Dauerweizen. Die einmalige Gründüngung hatte allerdings auf die mikrobiellen Parameter nach 7 Jahren keinen Einfluß mehr. C_{mic} und das C_{mic}:N_{mic}-Verhältnis zeigten eine ausgeprägte Saisonalität, im ersten Falle jedoch nur auf den Streifenanbauflächen. Die Ergebnisse zeigten positive Effekte des Streifenanbaues auf den Kohlenstoffstatus der Böden sowie auf mikrobielle Biomasse und Aktivitäten, auch wenn der Schnitt nicht eingearbeitet sondern entfernt wird. Dies spricht unter den gegebenen klimatischen Bedingungen für den Streifenanbau, insbesondere durch die Möglichkeit, den Kohlenstoffstatus der Böden durch einmalige Gründüngung auf Jahre hinaus zu verbessern.

Schlagworte: Monokultur, Streifenanbau, Sesbania, Vertisol, Mikrobielle Biomasse.

Summary

The effect of monoculture and Sesbania alley cropping systems (with constant removing of the prunings) and single-time residue input from alley crops or green manure on wheat yield was studied in a Vertisol of cool-humid tropical Africa. Seven years after the start of the experiment the A_p horizon was sampled four times during one growth period and soil basal respiration, microbial biomass C (C_{mic}) and N (N_{mic}), soil organic C (C_{org}), total soil carbohydrates (C_{hy}), soil pH and N were determined.

Alley cropping increased C_{org}, C_{mic}, basal respiration, qCO_2, the C_{mic}:C_{hy} ratio, and soil N, while under monoculture C_{mic}:N_{mic} and soil C:N ratios were increased. A single-time application of 5 and 10 t ha^{-1} Sesbania prunings resulted in an increase of C_{org} contents still detectable after 7 years. C_{org} contents of the green manured and fallowed wheat fields were higher than those of continuous wheat. In no case, however, did the microbial parameters exhibit any significant changes as a result of a single time organic residue application. The C_{mic} and C_{mic}:N_{mic} ratio exhibited seasonality, but for the former seasonality was observed only in alley plots. The results show positive effects of alley cropping on soil organic matter status, microbial biomass and activity even when prunings are removed, thus making alley cropping even more favourable in regions with scarce nutrient supply. This is further substantiated by the positive effects of single-time manuring and fallowing on soil C content.

Key words: Monoculture, Alley cropping, Vertisol, Microbial biomass, Soil carbohydrates.

2. Materials and methods

2.1 Site description

The field experiment was set up at Ginchi agricultural research station (Ethiopia, 09° 01' N and 38° 10' E, slope 0–3 %, 2200 m above sea level). The soil is classified as poorly drained, Pellic Vertisol (FAO), with 67 % clay, 18 % silt, and 15 % sand in the topsoil. The P content was 2 µg g^{-1} soil, pH 6.6, and the cation exchange capacity was 600 mmol kg^{-1} soil (KAMARA et al., 1989). The main rainy season extends from June-September (mean temperature 14.3° C) with some periods of flooding, light rains occur between February and May (16.8° C), and the dry season runs from October-January (14.7° C), receiving 64, 29, and 7 % of the total mean annual rainfall (1108 mm), in that order. Poor saturated hydraulic conductivity and plasticity limits of the soil, bimodality of the rainfall, topography, and seasonality of evaporative demand of the area prone this soil to seasonal perturbations.

2.2 Experimental layout

Monoculture and alley cropping systems were arranged in randomized complete block design in three replications, each with 4x17 m block size (divided in to 3 sub-plots of 4x5 m and inter spacing of 1 m), while the distance between replicate blocks was 2 m. To overcome possible interference from alley plants, monoculture blocks were established 15 m away from alley blocks.

In 1989, all sub-plots were grown by wheat, with the exception that one of the monoculture sub-plot was left bare fallow. *Sesbania sesban* was sown along the rows of alley blocks at a spacing of 1 m (from seedbed edge) and intervals of 0.5 m within a row. In 1990, one of the non-fallow monoculture sub-plots was grown by *Medicago truncatula* during off-season and turned into the same plot at flowering stage, whereas prunings of sesbania were chopped and incorporated into the respective alley plots at three rates (0, 5, 10 t ha^{-1}) shortly before the sowing period. From 1990 to 1997 alley plants were regularly pruned to a height of 0.5 m during the growing season (to reduce competition with companion crops), prunings were removed from the field, and wheat was produced on all plots without any type of fertiliser application or fallowing. Alley plots with 0 t ha^{-1} and unfertilised non-fallow (continuously cultivated) monoculture plots were used as a control.

2.3 Sampling

Five randomly selected samples were taken per plot from the A_p horizon (0–15 cm), bulked within plots, in November 96 and 97 shortly before harvest, when soil was dry and wet from unusual rainfall, respectively. Two additional samplings were carried out when soil was moist in March 97 and water saturated in July 97 a few weeks before and after tillage operation, respectively. Timing was carefully planned to represent major soil perturbation regimes. Roots and other pieces of undecomposed materials were removed, soil of each replica was placed in a separate air permeable polyethylene bag, air-shipped to Austria within 4 d under ambient conditions and immediately processed. Moisture was determined (105° C, 24 h) after sieving (2 mm), adjusted to 50 % of the water holding capacity (WHC) and the samples were aerobically incubated (in dark, 7 d at 22° C) for stabilisation prior to measurement of microbial parameters.

2.4 Analytical methods

Respiration was measured in moist samples, 50 % WHC, equivalent to 25 g oven dry soil. The CO_2 evolved was measured by an infrared gas analyzer (HEINEMEYER et al., 1989) and an hourly mean CO_2 output over 12 h was taken as basal respiration after the sample had reached a constant CO_2 production rate at 22 ° C ± 0.5. Soil microbial biomass was estimated by the substrate-induced respiration (SIR) method of ANDERSON and DOMSCH (1978).

For determining the C_{mic}:N_{mic} ratio, the extraction was performed based on the procedure given by VANCE et al. (1987) using 25 g of moist soil for the fumigated and non-fumigated samples. The samples were extracted with 100ml 0.5 M K_2SO_4 (30 min horizontal shaking at 200 rev. min^{-1}) and filtered (Schleicher and Schuell 595 1/2). The extracts were kept frozen (-18° C) until analysed. Organic C in extract or dry soil was measured by a continuous flow C analyser (C Mat 550 PC, Ströhlein, Germany) as described by INSAM (1996). The N in extract was converted to nitrate as outlined by EILAND and NIELSEN (1996) and N was determined conductimetrically (Wescan model 360 Ammonia analyzer, Alltech, Deerfield, USA). Soil N was determined from fumigated extracts and the C_{mic}:N_{mic} ratio was calculated as: $E_C/K_{EC} * K_{EN}/E_N$, where E_C and E_N are C and N extracted from fumigated minus non-fumigated sample, respectively. The K_{EC} and K_{EN} used were 0.45 (JOERGENSEN, 1996) and 0.54 (BROOKES et al., 1985), respectively. Soil pH was measured with a glass electrode using a 1:2.5 soil to water ratio.

Total soil carbohydrates were determined according to the method given by PICCOLO et al. (1996) and glucose equivalent carbohydrates were determined colorimetrically based on the Phenol-Sulphuric acid method (DUBOIS et al., 1956) at 490 nm (Perkin Elmer Lambda Spectrophotometer).

2.5 Statistics

Analysis of variance and simple linear correlation analysis were performed using the SPSS package (1994). Results presented are expressed on oven dry basis. Mean differences among treatments and between cropping systems were separated by Tukey's Honestly Significant Difference ($p < 0.05$).

Table 1: Soil microbial parameters and organic C in Vertisol after 7 years under alley and monoculture cropping. Treatments under alley cropping refer to a single time application of *Sesbania rostrata* prunings (alley cropping system) and a single time application of green manure in the case of the treatments called 'Medicago' and 'Fallow' (monoculture system) (values are means of sampling seasons and replications, n = 12; standard deviation is indicated)

Tabelle 1: Bodenmikrobiologische Parameter und organischer Kohlenstoff nach 7 Jahren Reihenanbau und Monokultur. Die Behandlungsvarianten in der Reihenkultur beziehen sich auf die Aufbringungsmengen von Schnitt von Sesbania rostrata, im Falle der Monokultur auf Gründüngung bei den Varianten ‚Medicago' und ‚Brache'. Die Variante Monoculture-continuous erhielt keine Gründüngung. Die Daten sind Mittelwerte über alle Saisonen und Wiederholungen (n = 12), die Standardabweichung ist angegeben

Cropping system	Treatments	C_{org} mg C g^{-1} soil	Basal resp. CO_2 g_{-1} soil h^{-1}	qCO_2 10^{-3} CO_2-C C_{mic}^{-1} h^{-1}	C_{mic}:C_{org} Percent	C_{hy} mg C g^{-1} soil	C_{mic}:C_{hy} Percent	Soil N mg g^{-1} soil	Soil C:N Ratio
	0 t ha^{-1}	19.59^a±0 80	2.08^a±0.17	1.59^a±0.004	1.82^a±0.15	6.54^a±0.47	5.48^a±0.65	2.53^a±0.29	8.26^a±0.81
Alley	5 t ha^{-1}	20.99^b±0.76	2.22^a±0.13	1.67^a±0.004	1.73^a±0.16	7.05^a±0.57	5.16^a±0.52	2.56^a±0.31	8.10^a±0.75
	10 t ha^{-1}	21.54^b±0.92	2.32^a±0.15	1.69^a±0.003	1.75^a±0.15	7.01^a±0.42	5.39^a±0.25	2.68^a±0.30	7.79^a±0.69
	Medicago	16.82^c±0.85	0.92^b±0.05	0.87^b±0.002	1.71^a±0.05	6.95^a±0.70	4.20^b±0.29	1.38^b±0.08	12.16^b±0.75
Monoculture	Fallow	16.54^c±0.54	0.83^b±0.07	0.81^b±0.005	1.69^a±0.03	7.08^a±0.25	3.95^b±0.19	1.31^b±0.08	12.61^b±0.92
	Continuous	15.17^d±0.49	0.77^b±0.07	0.08^b±0.005	1.72^a±0.04	6.17^a±0.21	4.24^b±0.30	1.17^b±0.06	12.97^b±1.04

Values within the same column are significantly different when followed by different letters.

3. Results

After 7 years, plots amended with prunings or Medicago green manure maintained a slightly higher biomass C, basal respiration, C_{org}, C_{hy}, soil N, and qCO_2 than the respective control plots. Conversely, the C_{mic}:C_{org} and C_{mic}:N_{mic} ratios tended to be higher in control plots than in treated plots. These differences, however, were not significant with the exception of C_{org} (Table 1). Plots manured with 10 t ha^{-1} Sesbania had a higher C_{org} than 5 t ha^{-1}, and C_{org} of Medicago plots was higher than that of fallow plots.

Alley cropping supported a significantly higher basal respiration, C_{mic}, qCO_2, C_{mic}:C_{hy} ratio, C_{org}, and soil N, while monoculture resulted in significantly higher C_{mic}:N_{mic} and C:N ratios (Table 1). Cropping systems or soil treatments did not significantly influence the C_{mic}:C_{org} ratio and C_{hy}. The soil pH remained stable throughout the experiment.

Trend analysis showed that some of the parameters, except qCO_2, C_{org}, pH, and C_{hy}, showed a specific seasonal pattern. Microbial biomass C, basal respiration, and soil C:N ratio were increasing in the order of March > July > November 1997 > November 1996, while C_{mic}:C_{org} ratio of March was > July > Nov.'96 > Nov.'97. The C_{mic}:N_{mic} ratios were highest in March, medium in November, and lowest in July samples. Nevertheless, only C_{mic} and C_{mic}:N_{mic} ratio exhibited a significant seasonality. C_{mic} (ranging from 257–411 and averaging 321± 45 µg C g^{-1} soil) was significantly higher in March than in November samples in the alley system, while no pronounced seasonality was observed in monoculture and between other sampling seasons in alley system (Fig. 1). The C_{mic}:N_{mic} ratio of March was higher compared to July in both cropping systems, whereas no substantial difference was found between other sampling seasons.

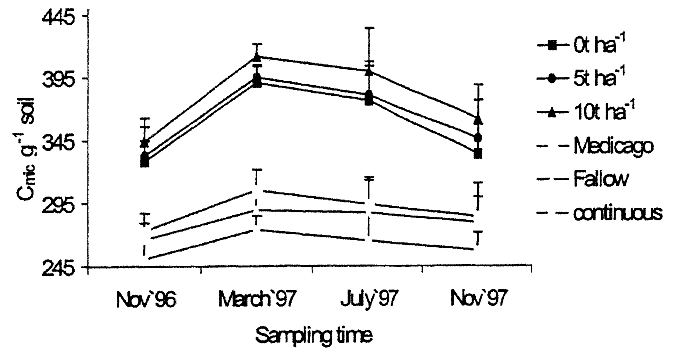

Figure 1: Microbial biomass in Vertisol under wheat monoculture (grey symbols) and wheat with Sesbania alley cropping (black symbols). The plots received different amounts of Sesbania prunings (5 t, 10 t) or green manure (in the case of 'Medicago' and 'Fallow' treatments) at the start of the experiment (7 years prior to sampling) (bars indicate standard deviations)

Abbildung 1: Mikrobielle Biomasse in Vertisol unter Weizen-Monokultur (graue Symbole) und Weizen mit Sesbania-Reihenkultur (schwarze Symbole). Die Versuchsflächen erhielten zu Beginn des Experimentes (7 Jahre vor der Probennahme) unterschiedliche Mengen von Sesbania-Schnitt (5 t, 10 t) oder Gründüngung (im Falle der Klee- und Brache-Varianten). Die Balken geben die Standardabweichung an

4. Discussion

4.1 Soil microbial parameters

Microbial biomass was within the range previously reported for agricultural soils (SINGH and SINGH, 1993) and own observation on other Ethiopian soils (LULU and INSAM, 2000). The tendency of treated plots to support a higher C_{mic} than the respective control plots suggests that addition of biodegradable OM of any form may increase C_{mic} (FLIESSBACH et al., 1994) for a considerable time. The high C_{mic}:N_{mic} ratio implies an abundance of fungi (INGHAM and HORTON, 1987) in all plots, but predominantly in monoculture plots. Views about the effect of dominance of fungal populations on SIR are diverse and still remain to be resolved (ANANYEVA et al., 1999). However, the strong negative relationship between basal respiration and the C_{mic}:N_{mic} ratio ($r = -0,82$, $p < 0.01$), indicates the effect of the fungal:bacterial ratio on the CO_2 evolution (SAKAMOTO and OBA, 1994). Hence, the higher qCO_2 in alley plots may be explained by its lower fungal:bacterial ratio or higher microbial activity due to higher substrate availability and quality (cereal + legume) (BAATH et al., 1995), or in the worst case might indicate some kind of stress (INSAM and HASELWANDTER, 1989; ODUM, 1985). From the present study it was difficult to ascertain which of the aforementioned assumptions were operating in the field at the time of sampling. However, considering the direct and indirect effect of alley plants on substrate status, soil qualities and microenvironments, it is more likely that C_{mic} and basal respiration were stimulated by influence of alley plants.

Various soil chemical (YEATES et al., 1997; BAATH et al., 1995) and biological (BARDGETT and MCALISTER, 1999) qualities are known to regulate the effect of the fungal:bacterial ratio. The lack of a shift in soil pH (partly due to the high buffering capacity of the soil) contradicts the shift towards a fungal dominated community. Nevertheless, the positive correlation of C_{mic}:N_{mic} ratio with the soil C:N ratio ($r = 0.82$, $p < 0.01$) suggests the segregation of microbial communities along the soil N gradient, and hints towards a higher N bioavailability in the alley cropping system.

In view of the duration of the field experiment and regularity of management practices, the constancy of the C_{mic}:C_{org} ratio across sampling seasons and treatments indicates that all plots have reached a steady state with regard to C (INSAM and DOMSCH, 1988). We noted similar trends on the same soil treated with mustard residues (LULU and INSAM, 2000) and other Ethiopian agricultural soils (unpublished). Rapid equilibration of tropical soils (within 3–5, and 5–10 years, in coarse and fine textured soils, respectively) has been reported previously (FELLER and BEARE, 1997). The C_{mic}:C_{org} ratio of Vertisol was lower than that reported for Central European soils (2.3 % for monoculture and 2.9 % for crop rotation plots) at steady state (ANDERSON and DOMSCH, 1989). It is unclear if microbial phenotypes of tropical soils are less C-efficient than those of temperate region soils or other environmental factors were at play.

The use of the C_{mic}:C_{org} ratio as an index of a steady state is based on the observation that C_{mic} fluctuates with the soil C pool, and remains stable when soil C input is equal to output. However, cases have emerged where C_{mic} was independent of soil C (WITT et al., 1998; ACOSTA-MARTINEZ et al., 1999). Because of the uncertainties concerning the universality of the C_{mic}:C_{org} ratio as an index of steady state, and for C_{mic} depending on the bioavailable C-pool rather than the bulk soil C (WITTER, 1996) if other factors are kept constant, we characterised the soil steady state by the C_{mic}:C_{hy} ratio. The C_{mic}:C_{hy} ratio revealed the establishment of alley and monoculture plots at different steady states and colonisation of alley plots by microflora that more efficiently converts substrate to biomass C. This coincides with ANDERSON and DOMSCH (1989) who have reported the development of microflora with higher yield coefficient in soils with diverse C-input (crop rotation) than monoculture plots. Even though for the first time we applied the C_{mic}:C_{hy} as an index of C steady state, and even if C_{hy} is conventionally classified as belonging to the labile soil C pool (PICCOLO et al., 1996), this application may have a limitation, because not all C_{hy} are readily available, or fully extractable from the soil matrix (CHESHIRE and HAYES, 1990).

4.2 Soil microbial seasonality

Since microbial seasonality and the shift in community structure was independent of treatments and cropping systems we were unable to relate microbial seasonality to a single environmental factor or a specific soil perturbation. WARDLE (1998) also observed no microbial stability difference between disturbed (agroecosystem) and undisturbed (forest ecosystem) environments and stated that the intensity and degree of disturbance has no destabilizing effect on C_{mic}. From our experience with tropical agricultural soils and the inconsistent temporal trends reported for the tropics (WARDLE, 1998) we suggest that C_{mic} seasonality in natural ecosystem is a function of multiple factors (climate, management, edaphon, etc.) that have spatial and temporal features, but which are not yet well documented. The significant seasonality in alley cropping plots might have been caused by seasonality of C inputs from alley plants (roots and exudates) and a flush of nutrients (due to mineralisation and alternate soil wetting and drying cycles).

4.3 Soil organic matter status

Accumulation of SOM under alley cropping system even without returning prunings into soil for the last 7 years can largely be attributed to massive residue input from the alley plant root biomass as enhanced by a mellowing process and repeated pruning stress that could inflict considerable death to, at least, fine roots. Similar results were reported for other alley cropping systems but with return of prunings into soil (CHANDER et al., 1998) and in fruit yards (HARON et al., 1998).

In view of the fast mineralization of Medicago and Sesbania litter (LUPWAYI and HAQUE, 1998a) and presumed rapid turnover rate of OM in tropical environment (AYANABA and JENKINSON, 1990), a medium-term effect of single time manuring on C_{org} was unexpected. Predictably, clay protection, existence of anaerobic phases of oxidation over an extended period, dominance of fungi that are C efficient but active mostly at oxic sites of the aggregates, the cool climate, and nutrient (N and P) availability might have slowed biochemical oxidation of SOM. The similarity in C oxidation loss between both cropping systems can be partially explained by a poor P supply of alley plants (LUPWAYI and HAQUE, 1998b), removal of nutrients with prunings, and considerable denitrification loss from the soil. Under the given environmental conditions, the higher N content in alley cropping system shows the capacity of the Sesbania plants to fix N even in perturbed soils and with successive pruning, and possible fixation of NH_4^+-N in the interlayer space of smectite clay (CORBEELS et al., 1999). Since current crop yield was independent of cropping system and C_{org} status, we may state that higher OM does not necessarily mean higher productivity, as the latter is a function of various environmental and biological factors.

5. Conclusions

Alley cropping with leguminous *Sesbania sesban* substantially increased microbial biomass, activity, C_{org}, soil N status, and enhanced microbial seasonality as compared to the monoculture system, even without returning prunings into soil for the last 7 years. Under similar management, soil type and climatic conditions, the alley cropping system appeared to be superior to monoculture in improving soil biological qualities and the overall results point towards possible removal of prunings for other uses. A medium-term (7 years) effect of the single time manuring practice was observed only in terms of an increased soil C content.

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