Organic inputs from agroforestry trees on-farms for improving soil quality and crop productivity in Ethiopia

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Abstract

Indigenous agroforestry trees and shrubs on farmlands are an under-utilized resource that can be used as green manures (GM) to alleviate declining soil fertility and productivity. The aims of studies described in this thesis were to investigate: (1) the seasonal dynamics in chemical contents of foliage from selected tree species potentially available as sources of GM, (2) rates and patterns of mineralization of nutrients during decomposition of leaves, (3) nutrient limitations for microbial processes in *Mollic andosols* from farm and forest land-uses using microbial respiration kinetics, (4) the utility of microbial respiration kinetics for characterizing the quality of plant materials, and (5) the effect of combined GM and fertilizer inputs on crop yield and soil properties. The studies used two leguminous (*Albizia gummifera* G.F. Gmel and *Milletia ferruginea* (Hochst.) Baker) and two non-leguminous (*Cordia africana* Lam. and *Croton macrostachyus* Del.) species.

Foliar contents of N, soluble polyphenols (PL) and condensed tannin (CT) were higher during the wet season while those of K and lignin were higher during the dry season. Green leaves had higher N and P contents while senesced ones had higher contents of K, cellulose, PL and CT. On average, 27% of N and 48% of P was resorbed during senescence. In a decomposition study that used leaves of *Albizia* and *Cordia*, *Albizia* had higher mass loss, N loss and release of CT than *Cordia*. However, N was immobilized for the first four weeks in both species. High rates of CT loss seemed to have facilitated decomposition in *Albizia* despite high initial contents of PL and CT in the leaves. Nitrogen was more limiting than P for the soil micro-biota suggesting the presence of adequate amounts of endogenous soil P. Addition of excess P resulted in respiration pattern with two peaks, suggesting different N pools being available over time. The substrate-induced respiration, specific microbial growth rate and microbially available P were higher for the farm; while the % total added C respired (49-69%) was higher for the forest land-use indicating increased C costs to utilize strongly bound nutrients. Under both laboratory and field conditions, 11%-44% and 10%-42% of initial leaf C was mineralised within a month, respectively, with the species ranking as: *Cordia* < *Albizia* < *Milletia* < *Croton*. Supplemental N and P had little effect on C mineralization. Green manure (GM) from the four species caused an increase in maize yield by 10-84%, with the increase being higher for GM from *Croton* and *Cordia* which apparently had higher P and K contents in their foliage than *Albizia* and *Milletia*. Measurable improvements in pH and soil organic C due to GM inputs were also observed at the end of the short–term (2 y) field trial.

Key words: Foliar nutrients, Agroforestry species, Land-uses, Mineralization, Nutrient Limitation, Microbial activity, Soil respiration, Green manure, Sub-humid tropical

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Contents

Appendix

Paper I-V

This thesis is based on the following papers, hereafter referred to by the respective Roman numerals:

I. Teklay, T., 2004. Seasonal dynamics in the concentrations of macronutrients and organic constituents in green and senesced leaves of three agroforestry species in southern Ethiopia. *Plant & Soil* 267:297-307.

II. Teklay, T., Malmer, A., 2004. Decomposition of leaves from two indigenous trees of contrasting qualities under shaded-coffee and agricultural land-uses during the dry season at Wondo Genet, Ethiopia. *Soil Biology & Biochemistry* 36: 777-786.

III. Teklay, T., Nordgren, A., Malmer, A., 2005. Soil respiration characteristics of tropical soils from agricultural and forestry land-uses at Wondo-Genet (Ethiopia) in response to C, N and P amendments. *Soil Biology & Biochemistry* (in press)

IV. Teklay, T., Nordgren, A., Nyberg, G., Malmer, A., 2005. Carbon mineralization of leaves from four Ethiopian agroforestry species under laboratory and field conditions. *(Submitted Manuscript)*

V. Teklay, T., Nyberg, G., Malmer, A., 2005. Effect of organic inputs from agroforestry species and urea on crop yield and soil properties at Wondo Genet, Ethiopia. (*Manuscript*)

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Introduction

Background

Declining soil fertility, a phenomenon that ultimately leads to soil degradation, has become a serious issue of global scale in the modern era (Lal, 2001). Soil degradation is a reduction in soil quality or the inherent ability of the soil to perform a range of productive, environmental and habitat functions (Karlen *et al.*, 1997; Scherr, 1999; Lal, 2001). In the context of soil degradation, a decline in soil fertility could be interpreted as the depletion of soil organic matter and plant nutrients (Syers, 1997), water holding capacity, soil biomass, pH, top-soil depth, aggregation (Scherr, 1999). Soil fertility has decreased in large areas of sub-Sahara Africa (SSA) due to a combination of high rates of erosion, leaching, removal of crop-residues and cow-dung, continuous cultivation of the land without adequate fertilization or fallowing (Syers, 1997; Lal, 2001; Tadesse, 2001). This is aggravated by the inherent poor fertility of most tropical soils (Sanchez, 1976; Koning and Smaling, 2005). Soil degradation is also associated with losses of decomposer biota and, consequently, with a decrease in litter decomposition (Tian, 1998). Hence most soils in SSA are generally deficient in N, P or both (Sanchez and Logan, 1992; Mafongoya *et al.*, 2000), and cannot support sustainable crop production without external inputs of inorganic fertilizers (Mafongoya *et al.*, 1998). In addition, soil organic matter (SOM) which is often considered a good proxy for soil productivity (Koning and Smaling, 2005) has declined in many SSA soils, and ecosystem functioning of microbes in these soils is being limited by organic C (Sanchez and Jama, 2002). Consequently, SSA has experienced a decrease in overall food production per capita, with soil fertility decline being recognized as the fundamental biophysical cause for declining food security in smallholder farms (Sanchez *et al.*, 1997; Sanchez and Jama, 2002).

Ethiopia has a human population of *ca.* 74.0 million, of which 84% is rural (FAO, 2005), and growing at a rate of 2.6% per annum (World Bank, 2004). Agriculture is the mainstay of Ethiopian economy accounting for about 53% the GDP, more than 90% of the total export revenue (Bekele, 2001) and 85% of total employment (MOFED, 2002). However, the agricultural sector has been poorly performing due to a number of factors, the most important of which is severe soil (land) degradation and fertility decline (see Fig. 1), The problem is most serious in the highlands (>1500 m a.s.l) which cover 45% of the total land area (*i.e.* 100 million ha) and support 85% the human and 75% of the livestock population, and account for more than 90% of the regularly cultivated lands (FAO, 1986). Considerably high deforestation rate (150-200 thousand ha y^{-1}) have resulted in shrinkage of highland forest cover from 16% in the 1950s to 2.7% in the early 1990s (EFAP, 1994). This, besides its profound effect on soil degradation, has caused acute shortage of fuel and construction wood (EFAP, 1994; Tadesse, 2001). Consequently, Ethiopia has experienced alarming rates of soil erosion, averaging (sometimes exceeding) 100 t ha^{-1} per annum (FAO, 1986). This has resulted in one of the highest nutrient depletion rates in Africa, *i.e.* -41, -6, and -26 kg ha^{-1} yr^{-1} of N, P, and K, respectively (Stoorvogel and Smaling, 1990). In terms of output, soil erosion is estimated to cause a loss in production of 1% to 2%, and using crop residues and dung for fuel (*i.e.*, a diversion from their utility as farm inputs) leads to a further 1% per annum decrease in production (Hurni, 1993). Use of commercial fertilizers to replenish nutrients is very low; with the average rate of fertiliser application (1997 base year) being 11 kg ha^{-1} of cropped land against 9 kg ha^{-1} for SSA, and 90 kg ha^{-1} worldwide (Dudal, 2002). Although the demand for fertilizer is growing steadily (World Bank, 2004), the high financial costs and other practical issues discourage farmers from using them. Increase in production through expansion of cultivated areas is limited due to the unavailability of unclaimed arable land (especially in the highlands), and to climatic and soil constraints. The need for land to accommodate the increasing human population has been primarily catered for through re-division and reallocation of existing holdings, thus increasing the intensity of land-use pressure (Admassie, 1995)

In the long-term, population pressure dictates that efficient, high-input systems must be developed (Myers *et al.*, 1994) and fertilizer application is obviously an important strategy for alleviating nutrient depletion and increasing crop yield in SSA (Dudal, 2002). However, as mentioned earlier, most farmers either cannot afford or have limited access to fertilizers. In addition, fertilisers alone can not guarantee sustainable long-term productivity on many soils hence input of organic materials are needed to maintain SOM levels (Syers, 1997). In this respect, the role of agroforestry-based alternatives in improving soil quality and halting soil degradation while at the same time providing other multi-purpose benefits (*e.g.* timber, fuel-wood, fodder, fruits, C-sequestration) has long been recognized (Nair, 1993; Young, 1997). A number of recent studies have also highlighted the potential role of agroforestry systems in carbon sequestration at the global scale to mitigate global warming (Lal, 2004; Montagnini and Nair, 2004). In the context of soil fertility, an understanding of the soil biological processes (Scholes *et al.*, 1994) and the quality characteristics of organic inputs (Palm, 1995) is essential if locally available or on-farm materials (*e.g.* trees, shrubs, crop-residues) are to be used effectively. This understanding assists the manipulation of organic materials to improve the synchrony (Myers *et al.*, 1994) between nutrient release from plant residues and crop demand for nutrients. There is also growing interest in devising efficient combinations of organic inputs from agroforestry species and commercial fertilisers to improve soil properties and productivity (*e.g.* Gachengo *et al.*, 1999; Kwabiah *et al.*, 1999; Vanlauwe *et al.*, 2001; Nziguheba *et al.*, 2002). Improved application methods and targeting of inorganic fertilizers and organic inputs (*e.g.* trees, crop residues) not only conserves nutrients in the soil, but increases nutrient uptake efficiency (Gruhn *et al.*, 2000; Sanchez, 2002).

Soil biological processes- their role in carbon and nutrient cycling

The soil biomass is composed of micro-organisms (bacteria, actinomycetes, fungi, algae, and protozoa), invertebrate fauna, and of course plant roots (Alexander, 1977; Singh and Gupta, 1977). However, the decomposer microflora (microbial

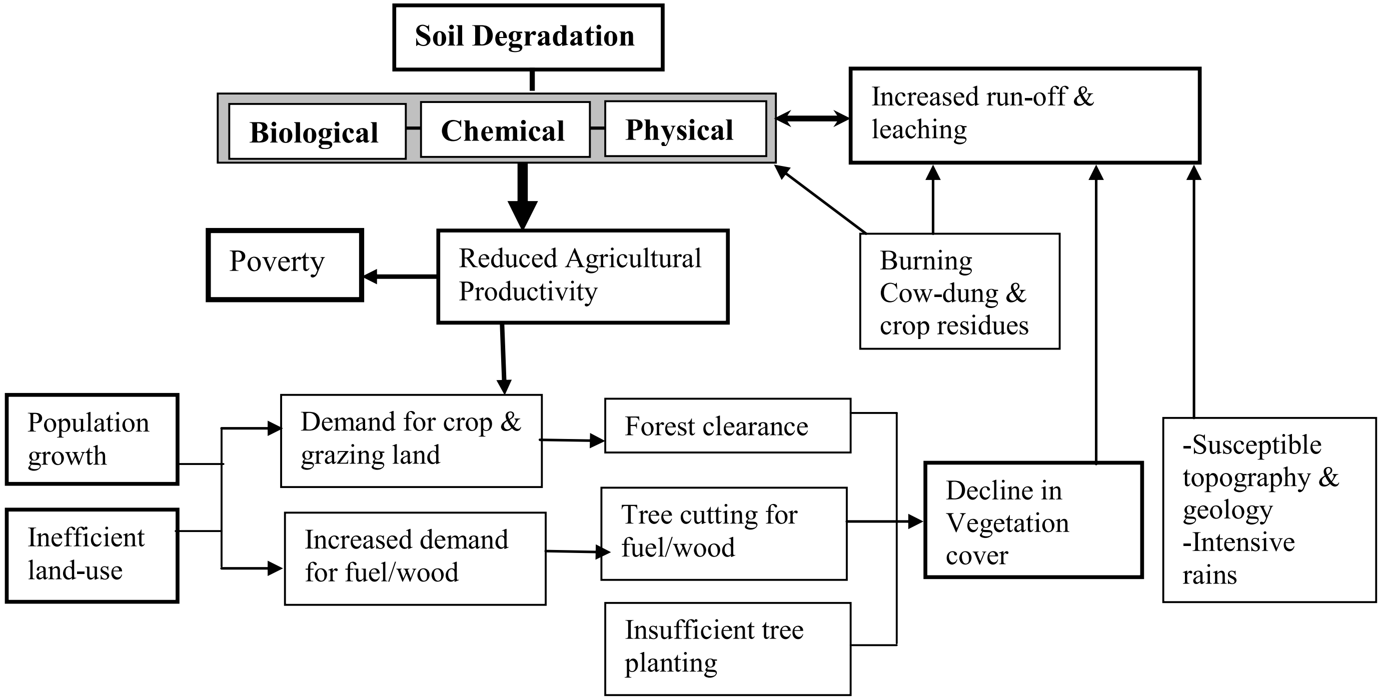

Figure 1. An illustration of the causes and processes of soil degradation in Ethiopia (Modified from EFAP (1994)). *NB*: Though biophysical factors are emphasised here, socio-economic & political factors (*e.g.* policies, tenure, market, and institutions) are also the other principal causes of soil degradation.

biomass) consisting mainly of bacteria and fungi is the primary agent within the soil ecosystem responsible for litter decomposition, nutrient cycling and energy flows (Wardle, 1992; Lavelle *et al.*, 1993; Tian, 1998). Micro-organisms are by far the major contributors to soil respiration and are responsible for up to 80-90% of the total soil CO_2 flux (Sigh and Gupta, 1977; Lavelle *et al.*, 1993). However, recent studies (*e.g.* Högberg *et al.*, 2001), indicate that root (including mycorrhizal) respiration could account for nearly half of total soil respiration. The microbial biomass, while a very minor fraction of the SOM (<5%), has a rapid turnover and regulates the cycling of organic matter and nutrients, *e.g.* N, P and S (Jenkinson and Ladd, 1981; Syers, 1997). The microbial biomass can solublize and mineralize nutrients from inorganic and organic sources (*e.g.* fixed P) otherwise considered unavailable to plants (Ilstedt *et al.*, 2003; Ilstedt and Singh, 2005) and serves as an important reservoir of plant nutrients. For instance, Anderson and Domsch (1980) estimated that microbial biomass contains 108, 83, 70 kg ha^{-1} or N, P and K, respectively in European arable soils. The activities of micro-organisms and soil fauna also serve to promote soil aggregation leading to reduced erosion and greater moisture infiltration (Woomer *et al.*, 1994).

The high turn over rate of microbial biomass also means that it reacts quickly to changes in management and is a sensitive indicator of change in SOM (Syers, 1997). The functional composition of the soil microbial biota varies according to land-use and vegetation cover (Dilly and Munch, 1998; Dilly, 1999). Land-uses that deplete organic C stock may cause a decline in the catabolic diversity of soil microbial communities (Degens *et al.*, 2000). Under normal conditions, only a small portion (<15%) of the micro-organisms are considered active and growing while the majority are in dormant state (Jenkinson and Ladd, 1981). However, forward-backward transitions between the two states could happen depending on availability of fresh organic C substrate and/or nutrients (Blagodatsky and Richter, 1998; De Nobili *et al.*, 2001; Stenström *et al.*, 2001).

The role of micro-organisms in nutrient cycling and energy processes of soil ecosystems has been measured by many methods, the most widespread being indirect methods such as fumigation-incubation (Jenkinson and Powlson, 1976), fumigation-extraction (Vance *et al.*, 1987), and substrate-induced respiration or SIR (Anderson and Domsch, 1978). The SIR method, which is employed in this thesis (Papers **III** & **IV**), measures the respiratory response of metabolically active components of the microbial community (to added organic C, usually glucose), and is directly correlated with the size of the active microbial biomass (Anderson and Domsch, 1978). The method has been used (adapted) in a number of studies mostly from temperate and boreal climates to assess pollution effects of heavy metals (Nordgren *et al.*, 1988; Palmborg *et al.*, 1998), prediction of decomposition or characterising the quality of plant materials (Beare *et al.*, 1990; Neely *et al.*, 1991; Marstorp, 1996); to estimate the pool of bio-available nutrients and for a fast and qualitative detection of nutrient deficiency (Nordgren, 1992; Vesterdal, 1998; Demetz and Insam, 1999); and to assess nutrient limitations to microbial activity in different land-uses (Dilly, 1999). There are fewer comparable studies from the tropics using SIR-based microbial respiration kinetics to assess nutrient and C limitation of micro-biota (*e.g.* Cleveland *et al.*, 2002; Ilstedt *et al.*, 2003;

Ilstedt and Singh, 2005; Teklay *et al.*, 2005; Paper **III**) or to determine decomposability of plant materials (e.g. Bernhard-Reversat, 1998; Nyberg *et al.*, 2000; Nyberg *et al.*, 2002; Sall *et al.*, 2003; Paper **IV),** but the number is increasing.

Soil microbial biomass, activity and diversity are regulated by, among many factors, the quality and quantity of C substrate, availability of nutrients, moisture, temperature, pH, oxygen supply, and soil texture (Jenkinson and Ladd, 1981; Kumar and Goh, 2000). Microbial growth is primarily limited by C availability in most soils (Paul and Clark, 1996; Kumar and Goh, 2000; Ekblad and Nordgren, 2002), though some studies also reported limitation by both C and N (Ekblad and Högberg, 2000; Allen and Schlesinger, 2004). It is the demand for C as an energy source for enzyme production and growth which primarily drives the processes of decomposition and mineralization (Vitousek *et al.*, 2002; Fontaine *et al.*, 2003). The complexity of added C substrates also determines the diversity and proportion of microbial biomass activated by the substrate (De Nobili *et al.*, 2003). It is believed that a sequence of complex interactions between a heterogeneous substrate occurs during the decomposition of plant materials compared to easily decomposed single substrates, *e.g.* glucose (Marstorp, 1996; Fontaine *et al.*, 2003). Microbial biomass and activity may also be limited by N or P (Wardle, 1992). While N is considered a limiting nutrient in temperate areas, P is considered more critical than N in many natural tropical systems (Couteaux *et al.*, 1995; Allen and Schlesinger, 2004; Cleveland *et al*., 2002).

While nutrient availability is considered to be a determinant of decomposition and microbial activity (Swift *et al*., 1979), microbial responses to addition (or availability from endogenous pools) of supposedly limiting nutrients to soil vary widely (Fog, 1988; Aggangan *et al.*, 1998; Hobbie and Vitousek, 2000). In most cases, addition of N had negative effects (Söderström *et al.*, 1983; Fog, 1988; Fisk and Fahey, 2001) or negligible effects (Fog, 1988; Prescott, 1995; Priess and Folster, 2001; Thirukkumaran and Parkinson, 2002), and less frequently a positive effect (Kelly and Henderson, 1978; Aggangan *et al.*, 1998; Goyal *et al.*, 1999). The 'negative' effects reported were mainly attributed to: (1) nitrogen-induced repression of lignolytic enzymes where fungal degradation of lignin is retarded, especially at advanced stages of decomposition when lignin plays the dominant role (Fog, 1988); (2) luxury uptake of N by micro-biota in excess of what is actually needed for their growth and maintenance (Prescott, 1995; Hobbie and Vitousek, 2000) and a relatively less CO_2 respired, as a result, could have been interpreted as 'negative or no effect' on decomposition, (3) polymerisation of N compounds with polyphenols and increased C retention by N (Söderström et al., 1983), (3) reduction of pH, hence lower decomposition, especially when acid-forming N-fertilizers are used (Maheswaran and Attiwill, 1989), and (4) reduction of CO_2 respiration due to diversion of C to microbial growth once N limitation is relieved, which could have been interpreted as 'retardation' of decomposition (Dilly, 1999; Schimel and Weintraub, 2003). Likewise, microbial responses to P addition also tend to be highly variable depending on a number of circumstances (*e.g.* Kelly and Henderson, 1978; Kwabiah *et al.*, 1999; Thirrukkumaran and Parkinson, 2002).

Other sources of variation between the different studies are attributable to differences in methods used, temporal resolution of measurements, choice of nutrients and substrates, the microbial parameters considered, and the duration of the experiment and the stage of microbial growth or decomposition when measurements were taken. Interactions between the type of nutrients applied versus site (or soil), species or type of C substrate have also been reported (*e.g.* Kwabiah *et al.*, 1999; Kuzyakov *et al.*, 2000; Schimel and Weintraub, 2003) and this may also probably reflect local and regional variations in soil chemistry. Most studies on nutrient limitations to microbial activity and decomposition focus on temperate and boreal soils, where N is considered a limiting nutrient, but in the few studies on tropical soils, P is presumed to be limiting. Nevertheless, it would not be appropriate to assume that all tropical soils are P limited, as P availability is site-specific and variable.

Trees on farms in enhancing soil quality and productivity

One variant of the multitude of tropical Agroforestry systems and practices is the 'scattered trees on crop land' system which consists of growing agricultural crops under scattered (dispersed) or systematically-planted trees on farms and/or farm boundaries (Nair 1993). A synonym, mostly used to describe similar systems in the Sudano-Sahelian Zone of West Africa is 'parklands' where scattered individual mature trees occur on cultivated or recently fallowed fields (Boffa, 1999; Verheij, 2003). They are one of the most widespread traditional land-use systems in sub-Sahara Africa (Nair, 1993), and develop when crop cultivation on a piece of land becomes more permanent (Verheij, 2003). In such systems, a small number of species are often maintained and in some cases planted by farmers for their beneficial effects on soils and crop yields, for their use as sources of fuel-wood, construction materials, shade and other uses (Young 1997). The species diversity and complexity of such systems is determined by ecological conditions, *e.g.* high diversity in high rainfall areas (Nair, 1993) and, to some extent, by the socio-economic and cultural setting. Because of the variety of field realities encountered, the notion of parklands has been interpreted widely (Boffa, 1999), and it may encompass practices such as improved fallow, wind-breaks, live-fences and fodder banks.

Dispersed trees on-farms (and farm boundaries) or 'parklands' are common practices in Ethiopia (see Young, 1997) and cover a large part of the agricultural landscape in the study area, hence their emphasis in this thesis. However, despite the significance of their contribution to the livelihood of rural people, they have received little attention in the research and development arena. Only a few studies have been conducted in Ethiopia with the aim of investigating the impacts on soil- and crop-related parameters beneath some commonly occurring indigenous trees species *e.g. Faidherbia albida* (Poschen, 1986); *Cordia africana* (Yadessa, 1998; Asfaw, 2002); *Milletia ferruginea* (Hailu *et al.*, 2000; Asfaw, 2002), and *Croton macrostachyus* (Ashagrie, 1998). These studies highlight the potential for trees in such systems to modify soil chemistry, but the use of trees as sources of organic inputs (*e.g.* prunings/ green manure and compost) with the intention of enhancing soil quality and productivity is yet another unexplored area.

For organic inputs from agroforestry species to have a significant impact on soil and crops (annual or bi-annual), they firstly, need to have sufficient biomass and nutrients to meet crop requirements (Palm, 1995). This depends on numerous factors including species used, provenance, density of trees, climate, soil fertility, season, age of leaves or plant, and frequency of pruning (Palm, 1995; Teklay, 2004; Paper **I**). Secondly, the nutrient release during decomposition of the materials should be synchronized with crop demand (Myers *et al*., 1994). The decomposition process itself is controlled by three interacting factors: the physical and chemical environment (*e.g.* climate, soil mineralogy), substrate quality and the decomposer biota (Swift *et al*., 1979; Lavelle *et al*., 1993). These factors operate at different scales of space and time and differ in importance (Lavelle *et al*., 1993). For instance, climate is the predominant factor controlling decomposition rates at global scale, while litter quality is more important at a regional scale, especially under tropical conditions (Meentemeyer, 1978; Coûteaux *et al*., 1995; Aerts, 1997).

The quality (of plant materials) is a function of the initial concentrations and relative proportions of nutrients (*e.g.* N, P), lignin (LG), polyphenols (PL), and to some extent also soluble carbohydrates and cellulose (Singh and Gupta, 1977; Swift *et al*., 1979; Palm and Rowland, 1997). Materials with high initial N and low lignin and polyphenols concentrations are presumed to decompose and release nutrients fast and are therefore considered to be of ‘high quality. Those with the opposite characteristics are considered low quality; to decompose slowly and often show net immobilization of nutrients (Swift *et al*., 1979; Palm, 1995; Young, 1997). Based on pre-determined critical concentrations of the above three constituents, a decision tree such as the one suggested by Palm *et al.*(1997) could be made to aid in managing organic resources and fertilizers (see Fig. 2**)**. The influence of litter quality on decomposition has been extensively studied, and various indices that related quality to decomposition (and to N mineralization) have been proposed by several workers. For instance, N release was reported to have been determined by initial N (Constantinides and Fownes, 1994), PL (Oglesby and Fownes, 1992); PL/N (Palm and Sanchez, 1991); LG (Melillo *et al*., 1982; Oglesby and Fownes, 1992); (LG+PL)/N (Fox *et al*., 1990); C/total P (Nziguheba *et al*., 2000).

Various studies from the tropics have also attempted to estimate threshold nutrient concentrations (in leaves or litter) at which nutrient release is inhibited or immobilized; *e.g*., 1.5-2.5% N (Fox *et al*., 1990); 1.7% N (Constantinides and Fownes, 1994); 2% N or C/N of 25 (Myers *et al*., 1994); 1.5% N (Seneviratne, 2000); 2.3%-2.8% N (Vanlauwe *et al*., 2002); and 0.24 % P (Palm *et al*., 1999). Generally, there is no uniformity of view as to which of the chemical parameters and indices are the best predictors of decomposition and nutrient release. This could be attributed to differences in species, plant part, age, number of species

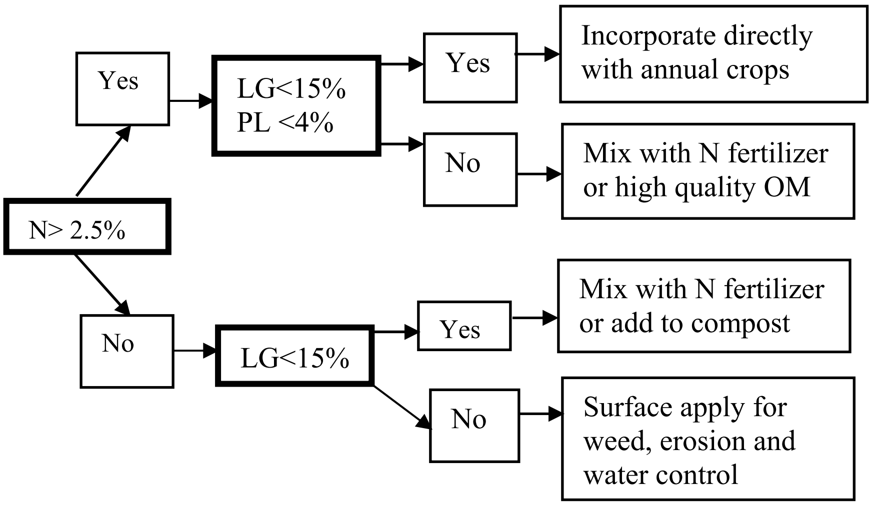

Figure 2. A preliminary decision tree that can be used for managing organic materials (OM) and inorganic fertilizers (from Palm *et al.* (1997))

considered, and method of analysis (particularly for polyphenols) between the different studies (Fox *et al.*, 1990; Constantinides and Fownes, 1994; Seneviratne, 2000). Moreover, the chemical control of litter decomposition also depends on the phase (stage) of decomposition (Aerts, 1997), *i.e.*, it might change in the course of decomposition, and likewise the relationships between the quality parameters and decomposition rates (Berg and McClaugherty, 2003). In addition to litter quality, management factors (*e.g.* method and timing of application, loading rates and quantities of prunings added) variably affect decomposition of prunings and uptake of released nutrients by crops (Kumar and Goh, 2000). For instance, Mafongoya *et al.* (1996) indicated that incorporation of pruning resulted in higher %N recovery and crop yield than surface application or mulching, while Xu *et al.* (1993) found no significant effect on maize yield between the two methods of pruning application. In the latter study, leaching of N was actually higher with incorporation. The timing of prunings application is another critical factor that regulates the synchrony of nutrient release with crop demands (Myers *et al.*, 1994). High quality prunings are thought to release nutrients too quickly, *i.e.* before crop demand for nutrients is high, while low quality pruning release nutrients too slowly or even immobilize nutrients during the cropping season. Mixing high and low quality plant material is suggested as one of the options to minimize nutrient losses and to achieve synchrony with crop demand for nutrients (Handayanto *et al.*, 1997).

The use of locally available plant materials from agroforestry species as farm inputs has a number of benefits (Fig. 3). The application of organic materials can be more advantageous than costly fertilizers by affecting many biochemical properties controlling nutrient cycling (Nziguheba *et al.*, 2000). They contribute to increased microbial biomass (Wu *et al.*, 2000), SOM build-up, greater efficiency of fertilizer use (Palm *et al.*, 2001), improved soil physical properties (Vanlauwe *et al.*, 2001; Dudal, 2002) and the supply of other macro/micro nutrients

(Nziguheba *et al.*, 2002) especially those not present in commonly used fertilizers. Organic inputs are also claimed to play a role in reducing P-adsorption (Nziguheba *et al.*, 1998) and soil acidification (Wong *et al.*, 1995). However organic inputs, even if applied at reasonable rates, could sustain crop yields only at limited levels (Vanlauwe *et al.*, 2001), with large amounts of biomass required to elicit moderate yield increase. Insufficiency of nutrients (especially P), the diversity and complexity of input chemical compositions and the difficulty of predicting patterns of nutrient mineralization to synchronize with crop demands all limit yield increase (Palm, 1995; Mafongoya *et al.*, 1998; Dudal, 2002); while immobilisation of nutrients (e.*g*. N) when low quality organic inputs are used may actually decrease

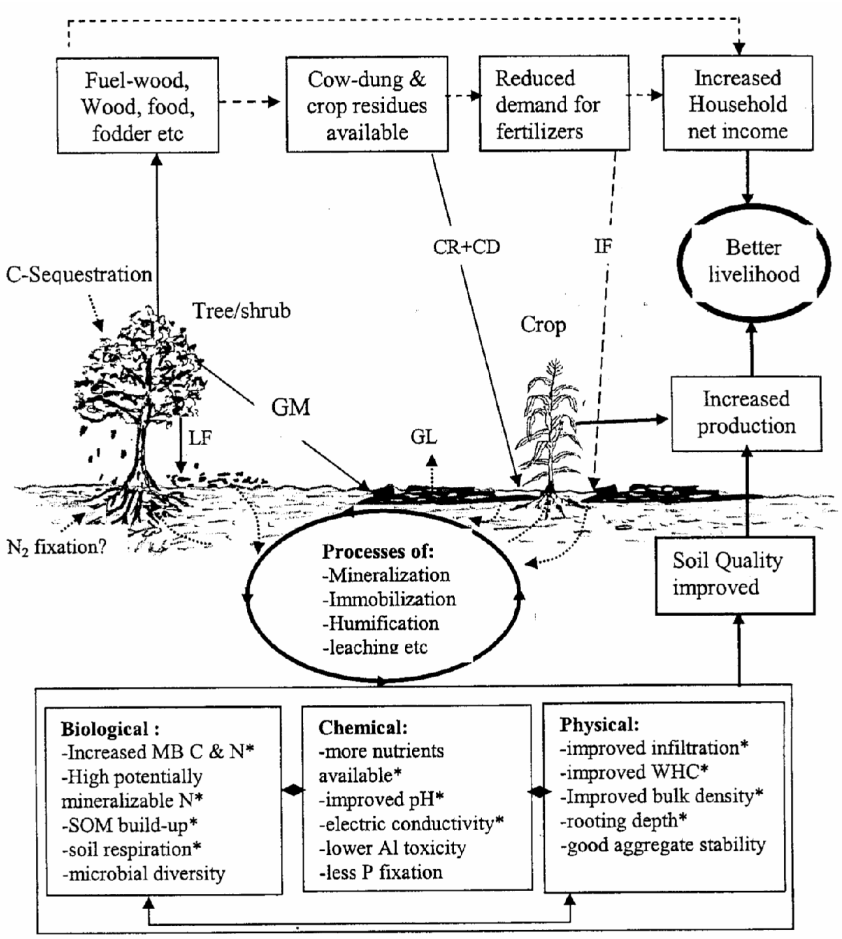

Figure 3. A theoretical model illustrating the use of trees on-farms in improving soil quality and their contribution to better livelihood of people (CD= Cow dung, CR= Crop residues, GL= Gaseous losses, GM= Green manure, IF= Inorganic fertilizer, LF= Litter fall, MB= Microbial biomass, WHC= Water holding capacity). Asterisk indicates properties that can be used as minimum dataset in assessing soil quality, according to, *e.g*., Karlen *et al.* (1997)

yields. Therefore, given the limitations associated with sole use of either organic or inorganic inputs, the judicious use of locally available organic resources combined with mineral fertilisers may be an optimal strategy for smallholder farmers (Buresh *et al.*, 1997a; Palm *et al.*, 1997; Giller, 2002).

In a preliminary survey of individual farmers and groups, conducted in the study area (Wondo Genet), about 80% of the farmers perceived decline in productivity of their lands while the remainder perceive either an increase or no change at all. More than 91% of farmers use commercial fertilisers either alone or in combination with animal manure. However, most farmers expressed the view that the cost of both fertilizers and animal manure is increasing and becoming unaffordable. Crop residue incorporation or application of green manure is not commonly practiced at Wondo Genet. A species ranking exercise using farmers' criteria of selection with respect to their potential value as organic inputs, their availability and other multiple uses showed that *Milletia ferruginea* (Hochst.) Baker*, Cordia africana* Lam., *Croton macrostachyus* Del., *Albizia gummifera* G.F. Gmel were among the most preferred trees species. *Albizia* and *Milletia* are leguminous while *Cordia* and *Croton* are non-leguminous. These species, considered in this thesis, are predominantly available on agricultural fields and farm boundaries, and as shade-trees for coffee growing.

Objectives

The overall aim of the thesis was to devise management options to better utilize and improve existing on-farm tree resources for improving soil fertility and achieving sustainable production. The specific objectives were:

- To characterise selected on-farm tree species in terms of the chemical properties of their leaves and to investigate the effect of season on the variation in nutrients and organic constituents in fresh and senesced leaves (Paper **I**).
- To determine the decomposition and nutrient release patterns for leaf biomass from tree species of contrasting quality and to examine how this varies under different land-uses (Paper **II)**
- To characterise soils under different land-uses in the study area in terms of their physical, chemical and biological properties, with particular emphasis on nutrient and C limitations to microbial activities and implication for nutrient availability to micro-biota and plants (Paper **III**)
- To determine the differences in C-mineralization rates of leaves from the selected tree species, representing different leaf qualities, under laboratory and field conditions, and to examine the effect of amending the soil with leaves plus N, P, or N+P on decomposition and microbial activity parameters. (Paper **IV**)

- To determine the effects of combined application of green manure from the selected agroforestry species and a commercial fertiliser (urea) on maize response (nutrient uptake, yield) and soil properties on farm. (Paper **V**)

Materials and Methods

Overview of study site

General Description

This study was conducted in the Wondo Genet area (7°06′ N and 38°37′ E, 1800-2100 m a.s.l.), located on the western escarpment of the central rift valley of Ethiopia, about 260 km south of the capital city, Addis Ababa (Fig. 4). The study area has a sub-humid tropical climate and receives a mean annual rainfall of 1247 mm (SD = 270) (Wondo Genet College Meteorological Report, 2000; unpublished). The rainfall pattern is bi-modal, with short rain season between March and May accounting for 28% of total rainfall, and long rain season between July and October accounting for more than 50% of total rainfall.

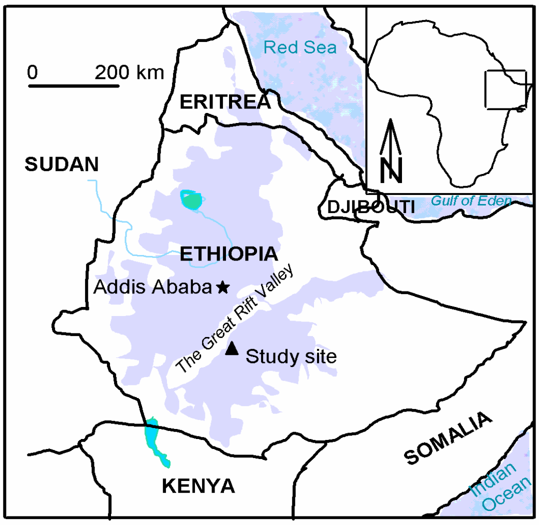

Figure 4. A map of Ethiopia (2.63-15.56° N; 32.49-48.85° E) showing location of the study site.

The mean monthly temperature is 19.5 °C with mean monthly maximum and minimum temperatures of 26.3 °C and 12.4 °C, respectively. Study **I** was based on periodic foliage sampling from coffee-shade trees inside Wondo Genet College of Forestry (WGCF). Study **II** was conducted on a crop field and coffee farm located inside WGCF. For study **III** soil samples were taken from farmers' fields in the surrounding localities (*i.e.* Wosha Soyama, Shesha Kekelle and Gotu-onoma) and a plantation forest located inside WGCF. Studies **IV** and **V** were conducted on soils from farm lands and using plant materials from the Gotu-Onoma locality situated about 6 km away from WGCF.

Geology and Soils

The underlying parent materials in the study area are of alkali trachytes and basalts, often overlain by volcanic ash deposits from the late tertiary period volcanics (Anon., 1973). The highland areas bordering the rift valley are characterised by moderately weathered dark-reddish brown soils with a clay-loam texture, which are all associates of the Rift Valley Volcanic soils (Lemenih, 2004). The soils at the lower elevation range of Wondo Genet are deep, loamy and relatively fertile *Mollic Andosols* (FAO, 1988). Classification of the soils was based on the work of Yimer (2002). The soils on the slopes of Gotu-Onoma where the on-farm experiment was conducted were less fertile and shallow in depth (<40 cm). *Andosols* are generally considered to be highly P-fixing but some soils which have received volcanic ash in recent geological history contain high levels of available P and thus are relatively fertile (Buresh et al., 1997b).

Vegetation and land-uses

The remnant forest vegetation at Wondo Genet can be categorised as 'Dry Afromontane' forests. Dry Afromontane forests have been defined as forests with a drought period of about half the year in one or two periods and an annual precipitation between 400-1700 mm. They occur in both the Northwest and Southeast Highlands of Ethiopia, at altitudes from 1500-2700 m, with average annual temperatures of between 14-20 ^{o}C and annual rainfall between 700 and 1100 mm (Teketay, 1996). According to elderly local informants, most of Wondo Genet area was covered with such forests until about the 1920s. However, high deforestation rates through the years have left only highly disturbed remnant forests which are now confined to the mountain slopes. A limited area of plantation forests that belong to WGCF and the former Munessa-Shashemene State Forest Development Project (established in 1969) also exist in similar locations as the natural forests. On the other hand, trees have been often maintained (and sometimes planted) on homesteads, farmlands and farm boundaries and give rise to, what could be described as a 'homestead' and/or 'scattered trees on crop lands' (parkland) type of agroforestry systems. While a variety of fruit trees and shrubs and cash tree crops (*e.g. Mangifera indica*, *Coffea arabica*, *Persia americana*, *Prunus persica*, *Rhamnus prinoides*, *Catha edulis, etc*) dominate the homesteads, the dominant species in the parklands include *Cordia africana*, *Albizia gummifera*, *Croton macrostachyus*, *Ficus* species, and *Milletia ferruginea*. Maize (*Zea mays* L.) sometimes followed by teff (*Eragrostis teff*) is the major grain crop grown on farms, while 'enset' (*Ensette ventricossum*), a staple food in the area and in most of southern Ethiopia, is grown in the homestead along with sugarcane (*Saccharum officinalum*), various root crops and vegetables.

Wondo Genet has one of the highest population densities (> 600 persons km^{-1} of arable land) in the country (based on the 1994 national population census) and farm sizes vary from 0.1 ha to 2.0 ha per household, the average being about 0.7 ha. In a preliminary survey of 35 farmers, average maize yields (*e.g.* hybrid BH140) at Wondo Genet varied from 1.2 to 4 Mg ha^{-1} per cropping season, with the mean of 2.4 Mg ha^{-1}. Maximum yields were realised when fertilizers were used at the full recommended rates (*i.e.* 100 kg Urea and 100 kg Di-ammonium phosphate).

Methodological aspects

*Characterizing plant materials and decomposition study (Paper **I** & **II**)*

In study I, (Paper **I**) foliage of species studied were sampled during the wet months of April-May 1999 and during the dry months of December 1999-January 2000. Fifteen sample trees for each of *Cordia africana*, *Albizia gummifera*, and *Milletia ferruginea*, were randomly selected and marked. Then, fully mature green leaves were collected from different crown positions; samples of senesced leaves were taken in a similar way. The experimental design had a $2^2 \times 3$ treatment structure, *i.e.*, there were 12 combinations, *i.e.*, 2 seasons, 2 leaf types, and 3 species. From the collections in each combination, five sub-samples were taken and analysed for total N, P, K, Acid Detergent Fiber-Lignin, total soluble polyphenols (PL) and condensed tannins (CT). Then, the change in concentration of nutrients and organics as leaves senesce, expressed as percentage of the concentration in green leaves, was calculated. This percentage change, particularly when used for N, P and K, is referred to as 'Resorption Efficiency' (Killingbeck, 1996) in this thesis when referring to nutrients in particular. Otherwise, terms like 'depletion' or 'enrichment' are also used to show either a decrease or an increase, respectively, in concentrations of organic constituents in senesced leaves relative to those in green leaves.

In the second study (Paper **II**), the decomposition and nutrient release patterns of *Cordia africana* and *Albizia gummifera* leaves was investigated using soil under farmland and shaded-coffee agroforestry land-uses using a 2 x 2 factorial arrangement of treatments in a randomised block design with three replicates and with repeated measurements taken over time. The experiment was conducted during a dry period spanning November 1999 to March 2000. Samples of 40 g air-dried leaves of each species were put in 20 cm x 30 cm, 2 mm mesh-size litterbags, then incorporated at 15 cm depth in soil under both land-uses and the residues were recovered after 2, 4, 8, 12 and 16 weeks. Residues were air-dried for one day, then oven-dried at *ca*. 40 ^{o}C for 24 h and weighed, and sub-samples were prepared for chemical analysis for same plant constituents as in Paper **I**. Single-or double-exponential decay or quadratic functions were fitted to describe patterns of decay or release of various leaf constituents and to quantify decomposition rate constants.

*Measurements of microbial activity, after addition of glucose or plant C substrates and nutrients (Papers **III** & **IV**)*

Respiration kinetics-Theoretical back-ground

The theoretical basis underlying respiration kinetics was that most soil ecosystems are C-limited (Paul and Clark, 1996), although nitrogen and phosphorus can also be limiting factors in some soils (Wardle, 1992; Cleveland *et al.*, 2002). A common method to determine limiting factors for the total native microbial community in soil has been to measure microbial respiration, since it has been assumed that the micro-organisms respire more when limiting substances are added (Alden *et al.*, 2001). When a source of labile C such as glucose is added, the microbial respiration rate increases rapidly (substrate induced respiration or SIR) by three to four times the basal respiration (BR), *i.e.* the soil's native CO_2 release (Anderson and Domsch, 1978). This initial respiration (SIR), occurring 1 to 5 h after adding substrates, and is not assumed to indicate microbial growth but merely that the micro-organisms are using the carbon for energy production (Alden *et al.*, 2001). The respiration rate stays at the initial SIR level for different lengths of time (the lag time L) depending on the condition of the soil (Nordgren *et al.*, 1988) and then starts to increase exponentially as the micro-organisms grow. This growth continues until carbon and/or nutrients, particularly N and P, limit further growth and a maximum peak (R_{max}) is reached (Fig. 5). This was used by Nordgren (1992) as a basis to elicit microbial response to addition of small doses of limiting nutrients (ΔN or ΔP) and hence to calculate microbially available N or P (Paper **III**).

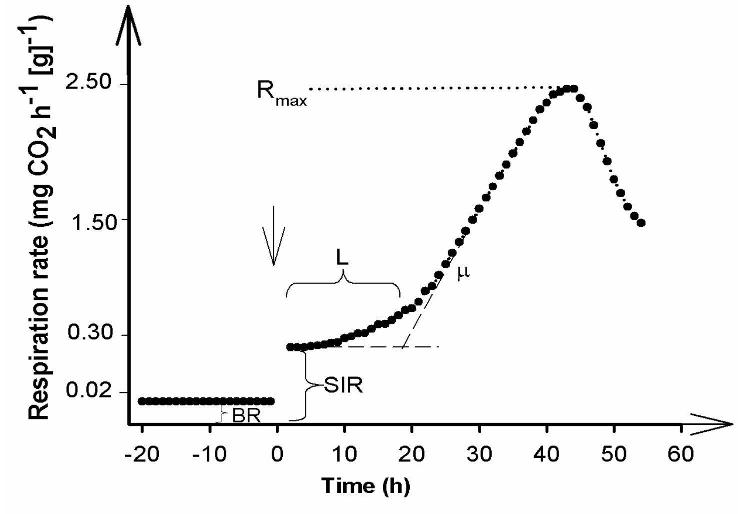

Figure 5. A model of soil respiration kinetics before and after addition of a C-substrate. The arrow indicates the time when the substrate was added. BR, SIR, L, R_{max} and μ are as defined in the text; [g] = gram of soil or organic material. The ordinate is assumed to be on a logarithmic scale (Adapted from Nordgren *et al.*, 1988).

*Nutrient limitations to soil microbial activity in different land uses (Paper **III**)*

Soils from a farm and forest land-uses were considered with the aim of assessing nutrient limitations to microbial respiration. Based on the variability in each land-use, 5 and 13 composite samples were taken from the upper 0-20 cm soil depth from the forest and farm land uses, respectively. Roots and other plant debris were removed from samples before storage at -18 °C until use. Sub-samples were also taken from each of the aforementioned field replicates and analysed for physical and chemical properties. Soil samples that had been storage at -18 °C were thawed overnight, sieved, thoroughly mixed, and then adjusted to a water potential of *ca*. -25 kPa. Then, 20 g sub-samples were weighed into each of 250 ml plastics jars and incubated at 20 °C in an automated respirometer (Respicond IV, Nordgren Innovations AB, Djäkneboda, Sweden) that continuously measures hourly rates of CO_2 evolution (Nordgren, 1988). Substrates containing glucose-C together with N and/or P in excess and limiting amounts were added to the jars after respiration had stabilized to basal levels. Based on the respiration kinetics obtained, the basal respiration (BR), substrate-induced respiration (SIR), specific microbial growth rate (μ), respiration maxima (Rmax) (Fig. 5), % of glucose-C respired, and microbially available N and P defined as 'the amount of the nutrients in the newly formed biomass'(Nordgren, 1992) in the soils were computed.

*Respiration kinetic to assess quality of plant materials and supplemental nutrient effects (Paper **IV**)*

A combination of laboratory and field experiments was used in this study (Paper **IV**) using plant materials from *Albizia gummifera*, *Milletia ferruginea*, *Cordia africana*, and *Croton macrostachyus*). Fresh intact leaves and air-dried leaves were used in the field and laboratory experiments, respectively. In the laboratory experiment, 0.5 g of dry leaf powders (corresponding to 15 Mg dw ha^{-1} of biomass) of each of the four species were used as sources of C in combination with 7.0 mg $(NH_4)_2SO_4$-N, or 1.4 mg KH_2PO_4-P or a mixture of the two to obtain overall ratios of C/N < 20 and C/P < 200. Soils that had not been amended with nutrients (only leaves added) provided the controls. The experimental design was completely randomised with a factorial treatment structure and three replicates, *i.e*., four species x four nutrient treatments x three replicates. Over a period of about a month, continuous hourly measurements of respired CO_2 were made conductimetrically using an automated respirometer (Respicond V) before and after application of treatments. The field experiment was conducted during a wet season in the field at Wondo Genet. It had a completely randomised design with four replications of 1 m^2 plots. The treatments were additions of fresh leaves of the four species and a control (no leaf inputs). Fresh leaves of each of the four species were incorporated into the top 10 cm of the 1.0 m^2 treatment plots at 5.0 Mg dw ha^{-1}. Then the CO_2 evolution rate (g CO_2 m^{-2} h^{-1}) was measured using an EGM-4 Infrared Gas Analyser connected to an SRC-1 Closed System Chamber with an internal diameter of 10 cm (PP Systems, 2002). Five measurements per day were taken from each plot, starting one day before the treatments were applied, and the experiment lasted for a month. For the laboratory and field experiments, the cumulative CO_2-C mineralization, the basal respiration (BR), substrate-induced respiration (SIR), specific microbial growth rate (μ), and respiration maxima (Rmax) were calculated.

On-farm study of combined green-manure and urea inputs (Paper V)

This experiment (study **V**) was done on a farmer's field. Soil samples were taken, just before the beginning of the experiment to depths of 0-20 cm and 20-50 cm and analysed for physical and chemical properties. The treatments were fresh green manures (GM) from *Albizia*, *Milletia*, *Cordia* and *Croton*, each combined with urea to give a total N input of 100 kg N ha^{-1}, with the GM contributing 75% or 50% of the total. Treatments containing just fertilizer (100% urea) and a control (no input) were included, thus making a total of ten treatments. The experimental design was a randomized complete block design with three replications conducted during two cropping seasons. The GM was applied to plots two weeks before planting, while urea was split-applied (*i.e.* half at sowing and the other half at knee-height, about 5-6 weeks after sowing). All treatments were applied only during the first crop season, and the 'residual' effect of the treatments (on crop performance and soil properties) was monitored for a second season. Maize was used a catch crop. At harvest, the fresh total above ground biomass (AGB) was weighed, separated in to components (*i.e.* stalk, leaves, and cobs) the fresh weight of each was also weighed. Sub-samples were taken for determination of %dry matter and nutrient concentrations. In addition, soil samples were again taken at final harvest and analysed for pH (in H_2O), organic C, and plant available P.

Chemical analysis of plant materials and soil

Ash content in plant materials was determined after ignition of oven-dried samples in a muffle furnace at 550 ^{o}C and total organic C was estimated to be 50% of ash-free dry-weight (Anderson and Ingram, 1993) and N was determined by the micro-Kjeldahl procedure (AOAC, 1980). However, in studies **IV** & **VI**, both C and N were determined by combustion using the automated procedures of a CN elemental analyzer (Europa Scientific, ANCA-NT Systems). Water soluble C in plant materials was determined on filtered cold water extractions (Thomas, 1977) using a Shimadzu TOC-5000 solution analyser (Shimadzu, Inc., Columbia, MD). Total P was determined colorimetrically using the ammonium acetate-molybdate ascorbic acid method (Murphy and Riley, 1962). Cellulose and lignin were determined by the acid-detergent-fibre (ADF) method (Van Soest, 1963). Soluble polyphenols (PL) were extracted using 70% acetone and determined gravimetrically by the ytterbium precipitation method (Reed *et al.*, 1985), and the %absorbance of condensed tannins (CT) was read at 550 nm.

Soil pH was measured potentiometrically in air-dried soil in distilled water (soil to-water ratio of 1:2.5 w/w). Total soil N was analysed by the Kjeldahl method (Bremner, 1996); plant-available P was extracted with Bray II solution (Bray and Kurtz, 1945) and the concentration determined by the ascorbic acid-molybdate method (Murphy and Riley, 1962); total P was determined by Flow Injection Analyser (Tecator 5020 Analyzer, Höganäs, Sweden) after wet digestion of samples using a combination of $HClO_4$-HNO_3-HF (Olsen and Sommers, 1982); soil organic carbon was determined by the Walkey & Black dichromate oxidation method (Nelson and Sommers, 1982); cation exchange capacity (CEC) by the ammonium acetate (pH 7) method (Sumner and Miller, 1996); soil texture was determined by the buoyoucos hydrometer methods; and oxalate extractable aluminium (Al_o) and iron (Fe_o) were analysed using Inductive Coupled Plasma-Mass Spectrometer (Elan 6100, Perkin Elmer, Connecticut, USA) following extraction with 0.3 M ammonium oxalate.

Data analysis

Data from all the studies was subjected to analysis of variance using the GLM procedures in SPSS for Windows (SPSS Inc., Chicago, IL, 1996), choosing either of the univariate ANOVA model (Studies **I**, **III**, **IV**) and/ or the repeated measures ANOVA model (Studies **II** and **V**). Partial correlation (study **II** & **V**) or Spearman's rank correlation (studies **III** & **IV**) were done to investigate relationships between variables. Comparison of means was done using either Tukey's t-test or Fisher's Least Significant Difference test. Statistical significance refers to $p < 0.05$.

Summary of Results and Discussion

Assessing quality of plant materials and leaf nutrient dynamics (Paper I)

In study **I**, the nutrient concentrations in fresh and senesced leaves of the three agroforestry species considered (Table 1) was generally higher than the reported mean value for trees from tropical regions, *e.g.* 14.6 ± 8.8 mg g^{-1} for N, 0.91 ± 0.67 mg g^{-1} P, but comparable to 209 ± 99 mg g^{-1} for lignin (Aerts, 1997). Comparable values of leaf chemical contents are also reported in many other studies, for example, 13-36 mg g^{-1} N, 124-313 mg g^{-1} lignin, 43-154 mg g^{-1} polyphenols in leaf biomass of various agroforestry species from different micro-regions of Kenya (Mugendi and Nair, 1997). Foliar contents of ash, N, soluble polyphenols, and condensed tannins were higher during the wet season while contents of K and lignin were higher during the dry season (Paper **I**). Increased level of N during the wet season in the present study could be the result of uptake of an increased pool of available rhizosphere N. Nitrogen fixation could also have contributed to increased N levels during the wet season, particularly for the leguminous species. This is in agreement with findings by Bell and Ward (1984), Tolsma *et al.* (1987) and others. In contrast, in a study on some tropical trees, Sharma (1983) found no significant seasonal variability for most nutrients. Potassium plays a vital role in the maintenance of osmotic potential (Bell and Ward, 1984), and the high concentration of K during the dry season in my study might be related to this phenomenon. The results on seasonal dynamics of polyphenols agree with that of Makkar and Becker (1998) who found a higher concentration of soluble polyphenols and condensed tannins under sub-humid than under arid tropical conditions.

Table 1. Average values (±SEM) of foliar leaf constituents classified by species, leaf type and season (n = 5)

Leaf	**Species**			**Leaf Type**		**Season**	
constituent	*Albizia*	*Milletia*	*Cordia*	Green	Abscised	Wet	Dry
Ash (mg g^{-1})	73.0	89.0	132.0	99.0	97.0	105.0	91.0
	(3.0)	(3.0)	(3.0)	(2.0)	(2.0)	(2.0)	(2.0)
N (mg g^{-1})	35.1	30.7	20.8	33.2	24.5	30.1	27.6
	(0.3)	(0.3)	(0.3)	(0.2)	(0.2)	(0.2)	(0.2)
P (mg g^{-1})	1.6	1.40	2.2	2.3	1.2	1.7	1.8
	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
K (mg g^{-1})	16.5	24.1	43.4	23.3	32.7	21.5	34.5
	(0.7)	(0.7)	(0.7)	(0.5)	(0.5)	(0.5)	(0.5)
CEL (mg g^{-1})	169.0	209.0	307.0	216.0	241.0	228.0	228.0
	(4.0)	(4.0)	(4.0)	(4.0)	(4.0)	(4.0)	(4.0)
LG (mg g^{-1})	260.0	205.0	241.0	236.0	235.0	198.0	273.0
	(9.0)	(9.0)	(9.0)	(8.0)	(8.0)	(8.0)	(8.0)
PL (mg g^{-1})	104.0	71.0	48.0	68.0	80.0	82.0	66.0
	(3.0)	(3.0)	(3.0)	(2.0)	(2.0)	(2.0)	(2.0)
CT (%Abs g^{-1}DM) [a]	90.0	48.8	18.9	46.3	62.4	59.3	49.5
	(1.5)	(1.5)	(1.5)	(1.2)	(1.2)	(1.2)	(1.2)

[a] No suitable standards were available to enable calculation of concentrations.

Although lignin was expected to show little seasonal variation, the 'decrease' in lignin concentration during the wet season observed in my study could possibly be due to an increase in other leaf constituents relative to lignin. It could also be an experimental artefact of sampling younger leaves that have less lignin content in the wet season.

The results from this study also showed that green leaves had higher contents of N and P than senesced leaves, while senesced leaves had higher concentrations of K, cellulose, soluble polyphenols and condensed tannins (Table 1). Similar results were reported by Constantinides and Fownes (1994) and Mafongoya *et al.* (1998) for N and P. Nitrogen and phosphorus in the foliage of the three species showed considerable resorption during senescence, and this was significantly higher for *Cordia* than for *Milletia* and *Albizia*. This is generally in agreement with similar other studies (*e.g.* Boerner, 1984; Aerts, 1996) that report higher N and P resorption for deciduous species compared to evergreen ones. On average, 27% of N and 48% of P in green leaves was re-translocated during senescence suggesting that P was probably more limiting for the tree species considered (Paper **I**). A firm conclusion can not, however, be drawn as legumes and non-legumes or deciduous and ever-green species were not equally represented, and in any case only a few species are considered here.

Overall, the relative percentage changes in concentrations of nutrients found in the present study for the three species are generally lower than values reported in the literature, for example: 61% N, 75% P, 84% K (Schlesinger and Hasey, 1981); 50% N and 52% P, averaged for several deciduous and evergreen species (Aerts, 1996); and 40% N and 70% P (Vitousek, 1998). The comparatively lower percentage resorption of nutrients (*e.g.* N and P) in my study could probably mean that these nutrients were less limiting to the trees (*e.g.* Tolsma *et al.*, 1987) in comparison to those used by the cited studies. Similarly, it may also follow that P was probably more limiting for the trees than N.

The pattern of enrichment or depletion for the organic constituents in the present study was very much confounded by interactions (Paper **I**). However, a more likely pattern evident from the results is the net enrichment of senesced leaves with organic constituents during the dry season. The higher total soluble polyphenols and condensed tannin concentrations found in senesced than in green leaves conform to findings in other studies (e.g. Schlesinger and Hasey 1981; Hättenschwiler and Vitousek, 2000). For instance, Schlesinger and Hasey (1981) found 35% more polyphenols, 26% more lignin but 32% less cellulose content in senesced litter relative to those in green leaves of *Ceanthus megalocarpus*. In contrast, in a synthesis of studies dealing with litter quality of tropical species, Seneviratne (2000) indicated that fresh leaves and litter contained comparable amounts of polyphenols. Other studies reviewed by Hättenschwiler and Vitousek (2000) reported substantial decreases in the number and concentration of low molecular weight polyphenols, and large increases in the protein-binding capacity of condensed tannins, in leaf litter compared with green leaves. Generally, as polyphenols are water-soluble and susceptible to leaching (Hättenschwiler and Vitousek, 2000), leaching by sporadic rain (from green leaves), might be one possible cause for the net 'enrichment' in senesced leaves but the exact cause or mechanism is difficult to ascertain. However, differences in methodology, species, site, and other ecological factors among the aforementioned studies make it difficult to make more detailed comparisons with the present study.

Decomposition and nutrient release patterns (Paper II)

In study **II** , *Cordia* had higher initial content of ash, K, P, cellulose, lignin and C-to-N ratio while *Albizia* had higher initial contents of N, PL, CT and C-to-P ratio (Paper **II**). *Albizia* had significantly greater mass loss, N loss and release of CT than *Cordia*. After sixteen weeks of incubation, *Albizia* and *Cordia* lost 59% and 43% of dry mass, 57% and 27% of N, 72% and 63% of P, respectively, and more than 90% of K in initially added amounts in litterbags (Fig. 6). This general trend in nutrient loss rates from decomposing leaves, i.e., K > P > N is consistent with findings in several other studies (*e.g.* Lousier and Parkinson, 1978; Palm and Sanchez, 1990; Ribeiro *et al.*, 2002). Nitrogen was immobilized for the first 4 weeks in most species-land use treatments, but ultimately, there was a net mineralization in all treatments.

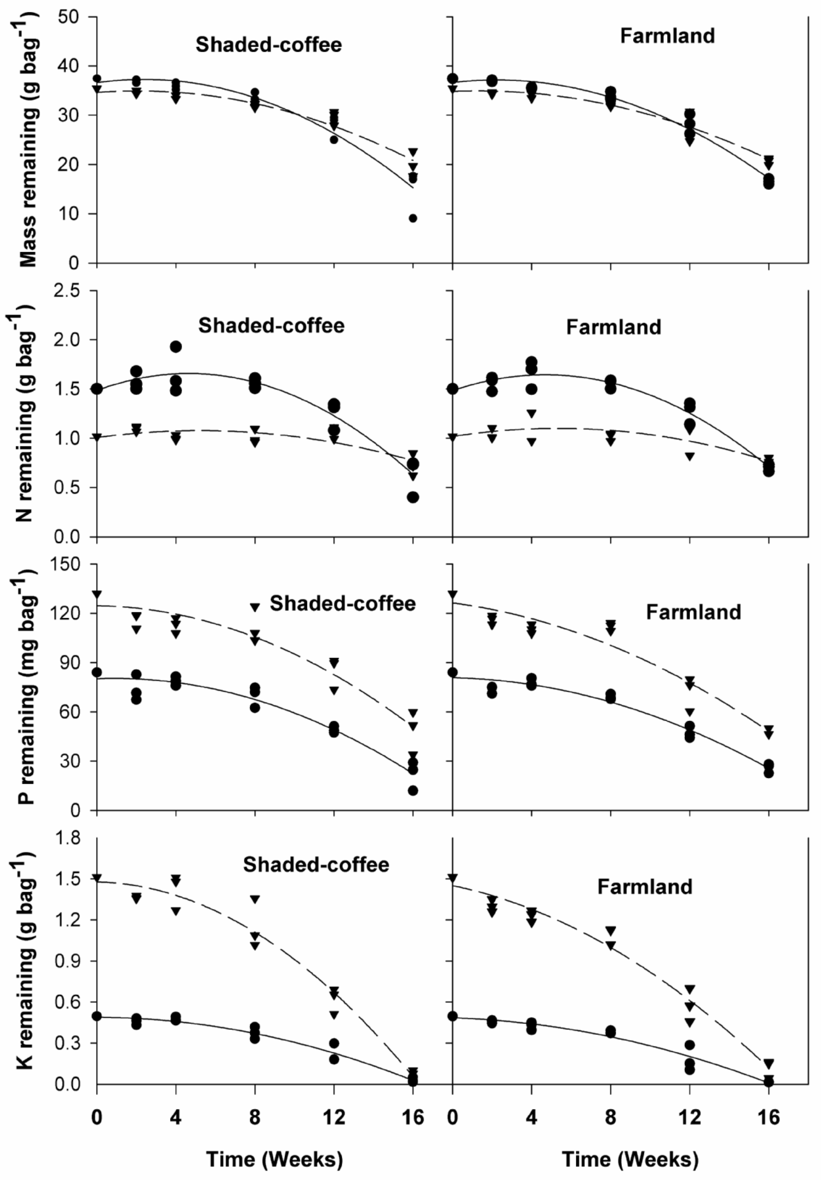

Figure 6. Mass loss and nutrient release patterns of leaves from *A. gummifera* (●) and *C. africana* (▼) incorporated in soils under two land uses during a dry season (n= 3; Initial amounts of leaves = 40 grams per litterbag, converted to ash-free dry weight)

As a significant portion of the P and K in leaves are inorganic forms, leaching might explain a big part of the P and K losses from the leaf residues. On a study using leaves from six agroforestry species, Kwabiah *et al.* (2001) reported that 54-82% of total P in leaves was in water-soluble forms, a significant proportion of which could be lost by leaching. Potassium is considered to be highly mobile element and is not incorporated in to organic structures, and hence is less affected by leaf chemistry and soil faunal activity (Tian *et al.*, 1992; Ribeiro *et al.*, 2002). Leaching of N is also not uncommon; as much as 25% of N, 50% of P and 85% of K in the leaves may be removed by leaching (Taylor, 1998). In the present study, higher rate of CT loss seems to have facilitated decomposition in *Albizia* despite higher initial PL and CT in the leaves of this species (*e.g.* 82% and 55% loss of PL in *Albizia* and *Cordia*, respectively). A number of studies have indicated that leaching of polyphenols could facilitate decomposition and nutrient release (Handayanto *et al.*, 1994; Handayanto *et al.*, 1997; Seneviratne *et al.*, 1998), and in the absence of leaching, some polyphenols are bound to proteins thus delaying decomposition and N release (Handayanto *et al.*, 1994). However, rapid loss of PL may not always be ascribed to leaching only, and degradation may play an important part (Bernhard-Reversat *et al.*, 2003). Moreover, it was also noted in my study that the concentration of CT increased against time in the decomposing residues of *Cordia* but decreased in those from *Albizia* (Paper **II**). This might support the claim that CT can have more impact than PL in terms of modifying the decomposition and nutrient dynamics (Handayanto *et al.*, 1997; Palm and Rowland, 1997). However, it was also observed in this study that *Albizia* leaves were preferentially eaten by termites, which may have resulted in the higher rate of mass-losses and losses of other constituents quantified based on loss of dry matter. Moreover, in a similar study I conducted under wet conditions, 39% and 56% mass losses were observed for *Albizia* and *Cordia*, respectively, *i.e.*, a reversed trend which suggested interactions between species and seasons (unpublished results).

The mass loss in the present study was adequately described by a double exponential model but a quadratic model provided the best fit for mass loss and losses of most of the other leaf constituents as well. The assumption behind the quadratic model was that some components could increase initially due to immobilization (*e.g.* N) or transformation of some substrates in to substances of lower decomposability. In addition to an increase in the absolute amount of N, the absolute amounts of cellulose and lignin also apparently increased during the first eight weeks of incubation, with the maximum at week four. This could be due to immobilization as in the case of N (Berg and Staaf, 1981; Fox *et al.*, 1990), formation of lignin-tannin complexes (Mafongoya *et al.*, 1998), but it is more likely that the method of lignin analysis was unable to distinguish between true lignin and partially humified products (Couteaux *et al.*, 1995). However, there are also a few studies where N concentration decreased with mass loss (Palm and Sanchez, 1990). Unexpectedly high rates of loss towards the end of incubation (Fig. 6), were attributed to stimulation of microbial activity and decomposition due to wetter conditions towards the 16th week, *i.e.*, towards a transition to the short-rain season. There was no significant land-use effect on any of the variables considered showing that, under drier conditions, tree cover might not affect decomposition, confirming findings in similar other studies done under tropical conditions (Vanlauwe *et al.*, 1997; Guo and Sims, 1999).

Carbon and nutrient limitation to soil microbial respiration (Papers III)

Study **III** was based on measurements of soil respiration (CO_2 evolved) after addition of glucose-C with nutrients (N, P) in excess and limiting amounts to soils from different land-uses, and the subsequent examination of microbial growth kinetics produced. Maximum respiration, which was assumed to correspond with maximum microbial biomass (Nordgren, 1992), was higher for C+N than for C+P addition. Although various studies suggest that P is more limiting than N for microbial and plant growth in (old) tropical soils (*e.g.* Duah-Yentumi *et al.*, 1998; Cleveland *et al.*, 2002), the pattern of respiration was modified more by N than P addition in this study (Fig. 7). This suggested that N is probably more limiting microbial growth than P in the systems studied. Similar findings were observed in other studies, *e.g.*, on forest soils from Malaysia (Ilstedt and Singh, 2005), and Germany (Dilly, 1999). Although *andosols*, which are often considered highly P-fixing, were used in this study, such soils can sometimes contain high amounts of available P in some sites near young volcanos (Buresh et al., 1997a). The presence of high amounts of labile indigenous P in young *andosols* from the rift valley region of Ethiopia was also reported by Duffera and Robarge (1999).

In the present study, a double-peaked respiration pattern was also observed when ample P was added to the soils suggesting a sequential extraction of different forms of N (with different ease of availability) by micro-organisms (Fig. 7b, 7d, 7f). The first peak is assumed to represent a smaller but easily available pool while the second peak is assumed to represent some recalcitrant but larger pool of nitrogen. Quantification of microbially available N and P, based on the first peak, yielded approximately 110-200 μg N g^{-1} and 17-72 μg P g^{-1}dw soil. Such estimates indicate that the microbially available fraction is smaller than total acid digestible pool of N or P, but substantially larger than 'plant available pools' determined by chemical extraction methods. This suggests that micro-organisms might be capable of extracting a wider N and P pool (both organic and inorganic), more efficiently than plant roots (Vesterdal, 1998; Ilstedt and Singh, 2005). The estimates of microbially available N and P obtained in this study are generally lower than those reported in other studies from boreal or temperate climates, *e.g.*, 0.15-0.40 mg N g^{-1} and 0.13-0.17 mg P g^{-1} OM (Nordgren, 1992); 1.07-2.40 mg N g^{-1} and 310-660 μg P g^{-1} soil (Vesterdal, 1998); 80-370 mg P g^{-1} soil (Demetz and Insam, 1999), but somehow comparable to the 50-300 μg P g^{-1} soil for the top 0-10 cm mineral soils from Malaysia (Ilstedt *et al*., 2003). However, differences in land-use and soil type, depth of sampling, whether computations were made on the basis of weight of soil or organic matter (OM) and other factors may complicate direct comparison of the cited studies with mine.

The results of this study also showed that, the respiration maxima and the total CO_2 respired were lowered when C was added alone (C-only) or with N and P (C+N+P) than either of N or P added separately along with C (C+N or C+P). Hence, during 18 d incubation after substrate addition, the cumulative CO_2-C respired, as percent of added glucose-C was about 49-69% for C+[N or P]

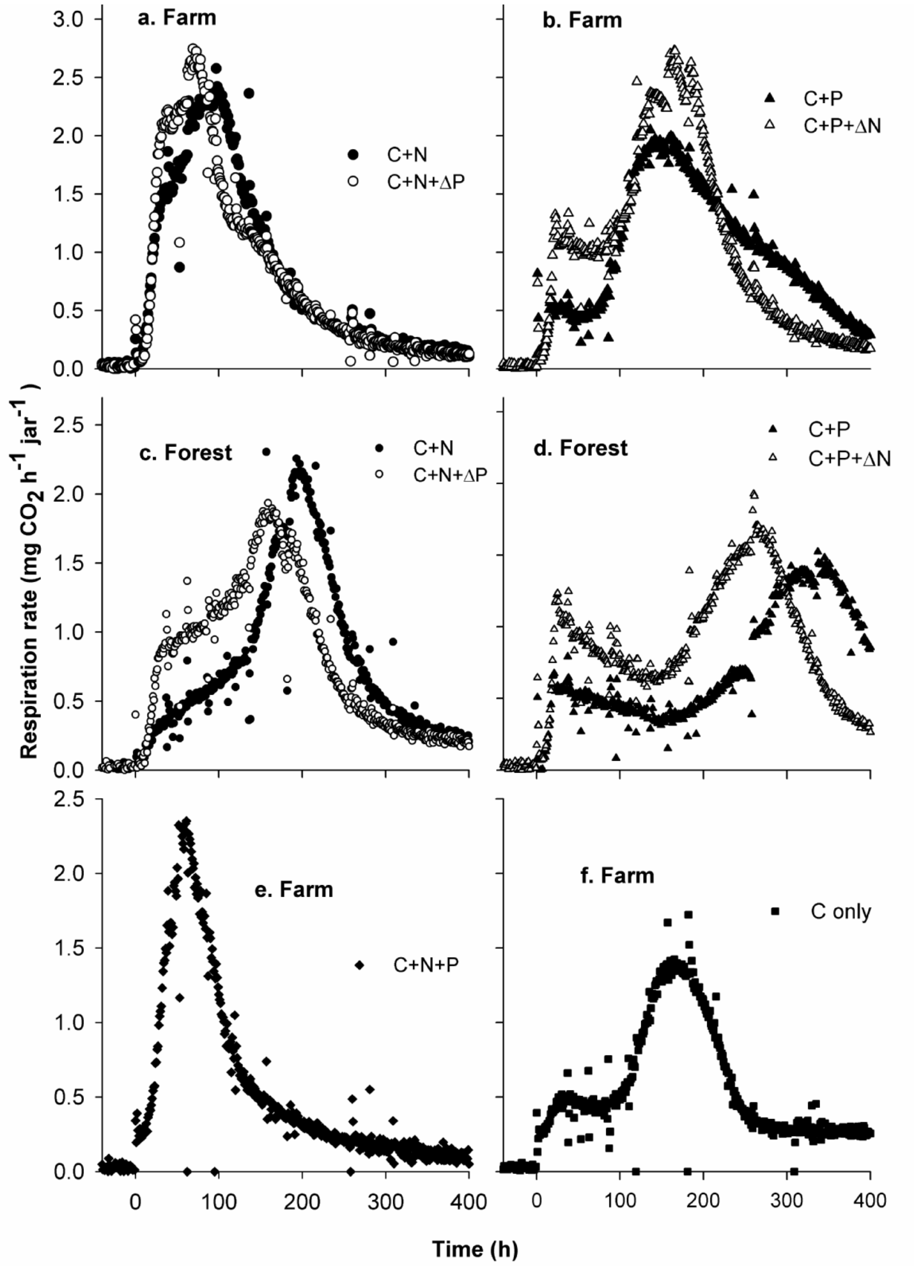

Figure 7. Microbial respiration kinetics of soils from two land-uses at Wondo Genet in Ethiopia, when glucose-C was added together with (a, c) excess N alone or plus small amounts of P or ΔP; (b, d) excess P alone or plus small amounts of N or ΔN; (e) excess N and P; (f) no additional nutrients.

treatments and 37-39% for C-only or C+N+P treatments. This suggested increased C-utilization efficiency, due to reduced respiratory costs and increased C incorporation in to microbial biomass, when both limiting nutrients were added. This is in agreement with results reported by similar other studies but from temperate regions (Zagal and Persson, 1994; Dilly and Nannipieri, 2001). For instance, Zagal and Persson (1994) using labelled C and N sources(^{14}C-glucose and Ca($^{15}NO_3)_2$) found that the residual organic ^{14}C remaining in soil after 84 days incubation was 36% and 40% for a 'low' and 'high' doses of N treatments, respectively. The same authors also found larger amounts of biomass ^{15}N at the end of the experiment in the 'high-N' than the 'low-N', where the reduction in total C-respired after adding N was attributed to incorporation of C in microbial biomass. When comparing land-uses, however, Dilly and Nannipieri (2001) found higher total C respired in arable than forest soils, *i.e.*, 35-38% and 25-31%, respectively, at the end of 11 days incubation, which is at variance with what I found in the study presented here.

In the present study, the SIR and specific-microbial growth rate (μ) were greater in soils from the farm while cumulative CO_2 respired was greater in soils from the forest (Paper III). This was attributed to relatively higher respiratory costs by microbes in the forest soils due to lower nutrient availability, and possibly due to the nature of SOM derived from plantation species considered to have litters of poor quality. For instance, Behera and Sahani (2003) reported lower microbial biomass C, N and basal respiration in soils from *Eucalyptus* plantation (presumed to contain high amounts of polyphenols and other secondary metabolites) compared to that from a regeneration forest. Variability in the composition of soil organic carbon (SOC) (Solomon *et al.*, 2002) and/or differences in microbial community structure and eco-physiology (Dilly and Nannipieri, 2001) due to (changes in) land-use may also explain difference in soil respiration between the two land-uses in my study.

Microbial respiratory response to addition of plant materials of varying quality with and without supplemental nutrients (Paper IV)

In study **IV**, leaves of *Albizia*, *Milletia*, *Cordia* and *Croton* were used as sources of C and nutrients. There was a considerable difference between the four species leaves with respect to their quality as substrates for microbial growth (Fig. 8a**)**. About 44%, 27%, 20%, and 11% of the C contained in the leaves of *Croton, Milletia*, *Albizia* and *Cordia*, respectively, was mineralized to CO_2 within a month. Similar trend was observed in the field experiment, *i.e.*, 42%, 17%, 15% and 10% of C initially applied as leaves of *Croton*, *Milletia*, *Albizia* and *Cordia*, respectively, was converted to CO_2. Maximum respiration rates occurred three days after incorporating fresh leaves in the field soil, with mean values ranging from 0.7 g CO_2-C m^2 h^{-1} for control soils to 2.0 g CO_2-C m^2 h^{-1} for *Croton treatments* (Fig. 8b).

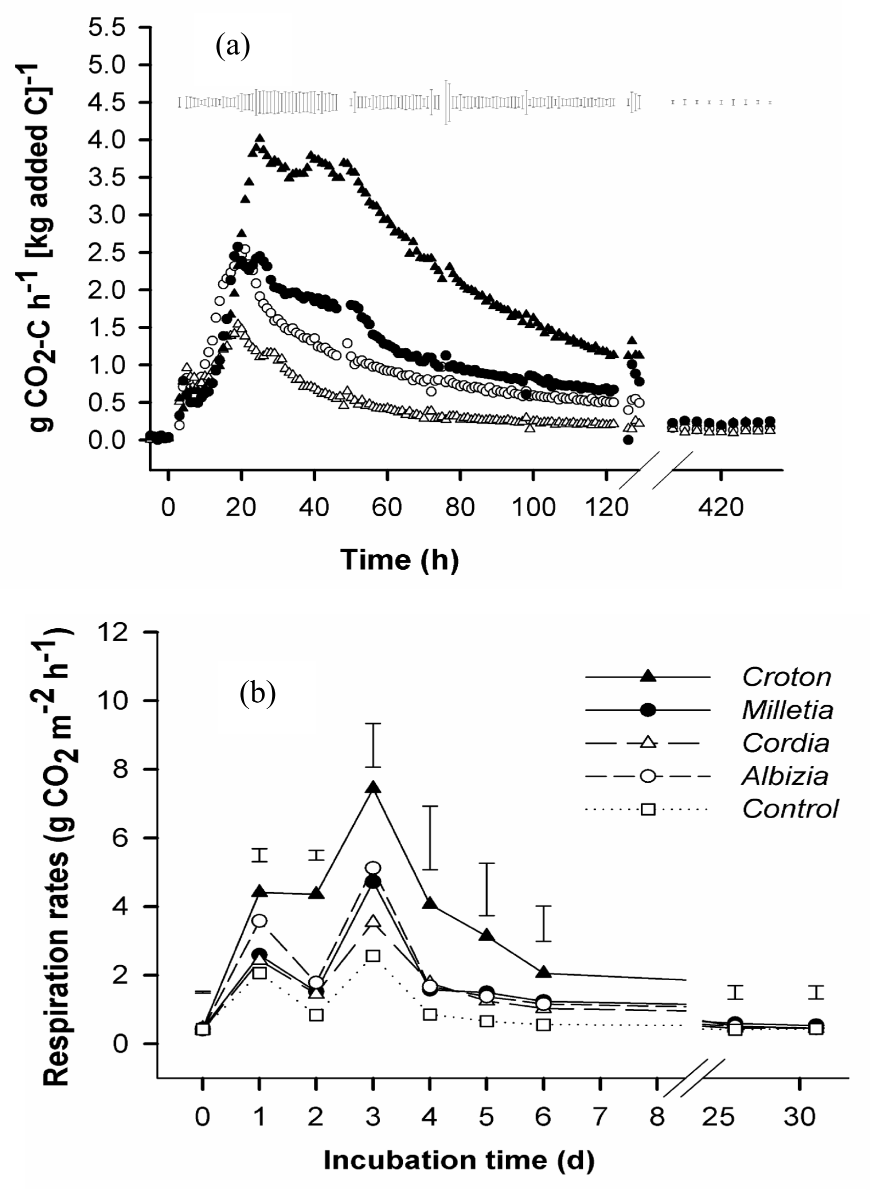

Figure 8. Temporal pattern of CO_2 evolution from the decomposition of green leaves in soils from Wondo Genet (a) under laboratory (n = 3) and (b) field conditions (n = 4); Bars represent Standard Error of Difference (SED).

The contribution of leaf C to the hourly amount of CO_2 evolved peaked at 52-79% in the fourth and fifth days (lowest for *Cordia* and highest for *Croton*); declined to 9-30% at day 26 (lowest for *Cordia*, highest for *Milletia*) and declining further to 0.6-16% after 31 days (lowest for *Croton* and highest for *Milletia*) (Paper

IV). The magnitude of total CO_2-released (as % of added C) in this study is much higher than the 0.7-3.0% of litter C evolved in 21 d incubation reported by Bernhard-Reversat (1998) using litter from 16 tropical species; but lower than those of Nyberg *et al.* (2002) who reported C-losses of 70-90% for *Sesbania sesban*. However, they are comparable with the 30-40% reported for a low quality *Grevillea robusta* green manure in 40-day field incubation in western Kenya (Nyberg *et al.*, 2002). In study **IV**, different respiration peaks were also observed, and were more obvious in some species' leaf treatments than others. Such peaks could reflect breakdown of various leaf constituents by microbes in accordance to their chemical complexity. In a similar study using plant materials, Marstorp (1996) suggested the multiple respiration peaks may be attributable to organisms simultaneously using two substrates upon which their specific growth rates (μ) and lag-phases differed. In comparison to pure substrates such as glucose (Paper **III**), addition of leaf substrates provided a diverse mix of organic substances and nutrients to decomposer micro-biota causing higher microbial activity (Paper **IV**).

Supplemental N or N+P mostly depressed the cumulative C-respired, and supplemental P either depressed it or had little effect. However, an increase in microbial activity, as reflected by shortened lag-time and/or increased specific microbial growth rates (μ) were observed when both N & P were added. This conforms to results in similar other studies that observed a decrease in respiration after addition of nutrients (*e.g.* Söderström *et al.*, 1983; Fog, 1988; Maheswaran and Attiwil, 1989; Aggangan *et al.*, 1998; Sall *et al.*, 2003). For instance, Sall *et al.* (2003) using tropical leaf litters in an *oxisol* found that total CO_2-C during 15 days of incubation was negatively correlated with total soil mineral N, and exogenous N had little effect on microbial biomass and activity. In contrast, many other studies have reported increased rates of respiration or decomposition after nutrient addition (Melillo *et al.*, 1982; Adedeji, 1986; Hobbie, 2000; Priess and Folster, 2001; Conde *et al.*, 2005). While in a study on Hawaiian montane forest soil, Hobbie (2000) found that lignin decay was increased by N addition, which is in sharp contrast to results from temperate forests. Therefore, there is at present no general agreement regarding the effects of nutrient availability on organic matter decomposition, and the introductory section of this thesis provides a detailed review of studies on the issue. Variation in conclusions between the different studies could be attributed to: (1) obvious differences in site, climate, plant species and litter quality, the type and amount of fertilizer added, the methods used (litter-bag *vs*. respiration based), whether studies were performed under laboratory or field conditions, and temporal resolution of the studies and/or (2) differences in the interpretation of same phenomena especially in those studies where respiratory responses to nutrient addition were measured (Schimel and Weintraub, 2003). For instance, when little respiratory response to addition of supposedly limiting nutrients (*e.g.* N) was observed, some studies assumed that the nutrient were not limiting (Maheswaran and Attiwill, 1989; Vance and Chapin, 2001), while others attributed the 'lack of response' or sometimes reduction in respiration to an increase in C-utilization efficiency (Dilly, 1999; Thirukkumaran and Parkinson, 2002; Schimel and Weintraub, 2003; Paper **III** & **IV**).

Various studies have also reported interactions between type of nutrients applied versus site (or soil), species or type of C substrate (*e.g.* Kwabiah *et al.*, 1999; Hobbie and Vitousek, 2000; Kuzyakov *et al.*, 2000; Schimel and Weintraub, 2003). For example, Hobbie and Vitousek (2000) in Hawaii found that addition of N or P to young (N-limited) soil had little effect on litter decomposition, while both N and P enhanced litter decomposition in an old P-limited soil. They also concluded that elevated litter N had little effect on decomposition. Similarly, Kwabiah *et al.* (1999) found that N fertilizer facilitated the decomposition of P-rich, N-poor plant materials, while P-fertilizer enhanced decomposition of N-rich, P-poor plant materials. Variable responses depending on species were also reported by Sall *et al.* (2003), where CO_2-C respiration was stimulated when inorganic N, in the form of $(NH_4)_2SO_4$, was added to leaf substrates from *Casuarina equisetifolia* but was retarded when N was added to those from *Faidherbia albida*.

Overall, given the very small magnitude of differences in %C respired between the nutrient amendments observed in my study, it could be asserted that the quality of C in leaves played the predominant role for C-mineralization in the species studied rather than supplemental nutrients. The C/N ratio and total N, in particular, and polyphenols (and to some extent lignin) and their ratios with N were the quality factors that strongly correlated with total C respired and specific microbial growth rate (Paper **IV**). This conforms to findings by Mafongoya *et al.* (2000), who found strong correlation between soil respiration versus C/N and lignin/N ratio of green manure. The apparent ‘lack’ of response to nutrient amendment could be due to the presence of sufficient nutrients to microbial demands in the leaves and/or soil, but other factors discussed earlier may also contribute to the observed results.

Combined green-manure and urea inputs (Paper V)

In study **V**, the agronomic importance and impact on soil properties of green manure from *Albizia*, *Milletia*, *Cordia* and *Croton* and their combination with an inorganic fertilizer (IF), urea, was evaluated under farm conditions for two cropping seasons (Paper **V**). During the first season, maize yield in the combined treatments increased by 10-84%, over the control, (Figure 9). However, the increase was significant ($p < 0.05$) in those treatments containing green manures (GM) from *Cordia* and *Croton*, *i.e.* the non-leguminous species with higher content of P and K in the leaves. Increasing the proportion of GM from *Cordia* or *Croton* (*i.e.* in the GM-Urea combination) from 50% to 75% tended to increase yield, while the opposite was true when the proportion of GM from *Albizia* and *Milletia* was increased. This could be explained by the higher content of P & K, but lower content of tannins in the leaves of *Cordia* and *Croton* compared to those of *Albizia* and *Milletia*. This was also supported by the strong correlation obtained between the aforementioned leaf constituents and season-1 grain yield (Paper **V**). The former two species also have faster release rates of P & K than the latter two (Gindaba *et al.*, 2004; Paper **II**).

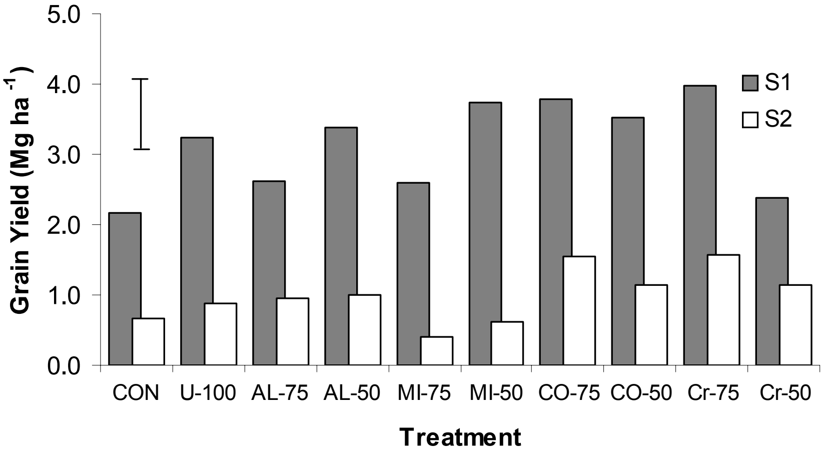

Figure 9. Grain yield of maize in two consecutive seasons (S1, S2) in an on-farm experiment using combined green manure and inorganic fertilizer treatments at Gotu-Onoma, Wondo Genet. Key to abbreviations: CON= Control, U= Urea, AL=*Albizia*, MI= *Milletia*, CO= *Cordia*, Cr= *Croton*; the numbers (50, 75, 100) refer to % contribution of the source, symbolized by letters, to the combined total N input, which was 100 kg N ha^{-1} (n= 3).

Based on initial leaf nutrient concentrations in green manure and predictive equations developed for the species considered (Gindaba *et al.*, 2004; Teklay T., unpublished; Paper **II**), a rough estimation of the amounts of nutrients that could have mineralized during the first crop was made. Accordingly, from the mixed treatments of all species except *Croton*, the estimated amounts of mineralized N (including that of IF) were within the range 46-71 kg N ha^{-1} (*Milletia* < *Albizia* = *Cordia*), with higher values when the proportion of fertilizer accounted for 50% of N applied. There were no obvious differences in yield that might be expected from the high N contents in the GM from the two legumes, indicating that N concentration alone did not control rates of decomposition and nutrient availability. This suggests that some other factors, in addition to N content of biomass, had a more profound effect, for instance, various possible interactions between GM and IF, contents of P and K, and N binding by polyphenols especially for *Albizia* and *Milletia* which had higher contents in their GM. For *Croton*, the predicted amount of mineral N (93-95 kg N ha^{-1}) was not only much higher than those from the other species, but it was slightly higher when the proportion of GM was 75% than 50%. This suggested that the GM from *Croton* had a significant contribution to the total mineralized N input. In the case of green manure from *Albizia* and *Milletia*, it is quite possible that the high amounts of polyphenols that leach to the soil system might have negatively impacted upon microbial activity, abundance, and altered N availability, *e.g.*, through complexation with N (Hättenschwiler and Vitousek, 2000), thus making N less available to the crop.

Comparisons based on predicted P, K release provide additional information for a sound explanation of treatment effects. The predicted amounts of mineral P and K from *Albizia* and *Milletia* were within the range 2.0-3.5 kg P ha^{-1} and 24-36 kg K ha^{-1} *(i.e. Albizia< Milletia*), generally very low to satisfy crop demands. The values for *Cordia* and *Croton* were comparatively high ranging between 5.0-8.7 kg P ha^{-1} and 69-106 kg K ha^{-1} (*i.e. Cordia* < *Croton*). Although these amounts of P alone might still not suffice for a substantial yield gain, it nevertheless constituents a significant proportion of the total P required by crop (in addition to P originally available in the soil). From this, it could be expected that, in the case of *Cordia* and *Croton*, increasing the proportion of GM to 75% would add a considerable amount of P and K, and make the two non-legumes good sources of such nutrients. In addition to P being available from the GM, some studies (*e.g.* Singh and Jones, 1976, 1990; Nziguheba *et al.*, 1998) also suggest that GM could indirectly increase P availability due to saturation of sorption sites by green manure P and/or competition for sorption sites between P and organic anions produced during decomposition of GM. Nziguheba *et al.* (1998) indicated that application of high quality *Tithonia diversifolia* significantly decreased P adsorption capacity of soil in western Kenya. In a study by Singh and Jones (1976), addition of organic materials with concentrations $\geq$ 3.1 mg P kg^{-1} decreases P sorption in soil, where as those with concentrations $\leq$ 2.2 mg P kg^{-1} would increase P sorption. Then, if this assertion would apply to the species used in this thesis, the high concentration of P in green manure from *Croton* and *Cordia* might have played a similar role, i.e., making more P available to the crop. Generally, increase in yield (above the control) due to application of green manure (or combined with IF) found in the present study is in agreement with many similar studies from the tropics (*e.g.* Gachengo *et al.*, 1999; Nziguheba *et al.*, 2000; Vanlauwe *et al.*, 2001; *e.g.* Nziguheba *et al.*, 2002; Kwabiah *et al.*, 2003). With some exceptional species such as *Tithonia*, fertilizer equivalence values of as high as 130% has been found (Kimetu *et al.*, 2004) implying that high quality organic inputs sometimes can even out-perform equivalent amount of inorganic fertilizers in improving crop yield. However, it has also been hypothesised that high quality materials, good for short term soil fertility might not necessarily build or maintain SOM in the long-term (Palm *et al.*, 2001).

In the present study, a decrease in yield over the control was observed (especially due to GM from *Milletia*) in the second season, but differences between treatments were generally not significant. A considerable amount of nutrients were in harvested above-ground biomass, *i.e.*, 99-162 kg N ha^{-1} and 9-16 kg P ha^{-1}, during the first crop alone, which in most case was higher than total N and P in added GM, with the exception of *Croton* in some cases. About 34-46% of N and 48-65% of P in above-ground biomass was in grains, while the rest was in stovers. A comparable range of N uptake by maize (42-157 kg N ha^{-1}) from prunings was reported from alley cropping experiments in a sub-humid highland central Kenya (Mugendi *et al.*, 1999). In the present study pH and SOC generally increased, but total soil N did not change appreciably, and available P decreased at the end of the second cropping season in comparison to initial soil properties. This improvement in SOC in such a short time scale would highlight the potential of GM resources for long-term sustainability and for carbon sequestration, although addition of external P is found to be almost a necessity to improve crop productivity. The amount of GM used in this experiment (*i.e.*, 1.3 to 3.0 Mg ha^{-1}), assuming leaf biomass harvest plus litter fall of a total 6 kg^{-1} dw per tree over two years, would necessitate a tree density of approximately 200-500 trees ha^{-1} on farm, farm boundaries and other suitable niches in the farm landscape. This may be practical under future management, especially in light of increasing concerns over land degradation and climate, the growing demand for fuel/wood and other non-timber products. Such future tree management options may need to come up with efficient arrangement of the tree component so as to minimize the trade-offs of competition for water, nutrients and light between trees and crops. Under current on-farm tree density of about 20 trees ha^{-1}, only 400-1000 m^2 land would benefit from GM input combined with inorganic fertilizer (NB: recycling of crop residues not being accounted here). This would mean that farmers should apply the GM to plots were fertility decline is severe or/and for production of high value crops. To go beyond that, on-farm tree cultivation and management needs to be increased considerably.

Major conclusions and future outlooks

In natural ecosystems, litter fall, root turnover and exudates, and N-fixation are the major pathways of nutrients and organic matter input to the soil. In managed agricultural systems, returns through such pathways might not be enough to compensate for losses in harvested products and other avenues. Additional inputs in the form of green manure from locally available trees and shrubs, in various mixture with inorganic fertilizers, was emphasised in this thesis. Based on the location- and species-specific studies presented in this thesis, the following major conclusions were made.

The nutrient concentrations in the foliage of many trees and shrubs species in the agricultural landscape of southern Ethiopia may be high enough for use as green manures. However, considerable quantities of nutrients, especially N and P, are re-translocated to perennial parts when leaves senesce, with the litter being enriched with organic constituents especially tannins which can retard decomposition. Therefore, green leaves (prunings) would be more effective as organic inputs than litter (Paper **I**). The practicability of this depends on how much foliage could be pruned without compromising the photosynthetic capacity of the trees/shrubs. The amount of pruned biomass that could be potentially available also depends on tree density, how fast nutrients are released to the soil (Paper **II**), and on the soil properties (Paper **III**). Variations due to species and seasons also have crucial role in modifying the quality of plant materials.

Land-use effects, particularly the presence or absence of tree cover had little effect on decomposition during the dry season. There was net mineralization of N and P from leaves/ green manure for the studied species highlighting their potential to replenish soil N and P which are presumed to be deficient in most tropical soils. However, interpretation of the process of nutrient release from different quality plant materials was much more complicated than could be predicted from initial concentrations of nutrient and organics. Mass loss and release of N could sometimes be comparatively high in species with high N and tannin contents (e.g. *Albizia*), suggesting rapid loss or degradation of the tannins in this leaf material. The nature and mode of release of tannins seem to be more important than the initial amounts or concentrations *per se*. However, once released into the soil system, there is uncertainty as to what effect such compounds (tannins) from the species considered may have, especially on soil micro-biota and nutrient availability.

Decisions on the type and amount of nutrient inputs to the soil depend on what nutrient (s) is/are actually limiting microbial biomass and activity. On the soil studied (*Mollic Andosols*), N could be more limiting than P for most microbial processes, which seems contrary to the conventional belief emanating from the P-fixing nature of such soils. Examination of the microbial respiration kinetics indicated that micro-organisms may not only access a much larger nutrient pool than plants, but can also sequentially extract different forms of nutrients over time, if provided with a labile carbon substrate (Paper **III**). The microbial respiration kinetics also proved to be a valuable tool in characterizing plant materials according to their qualities, which were also confirmed by a field experiment. Short term CO_2 respiration measurements could also be correlated with fast changing inorganic nutrient pools such as $NH4^+$ (Nyberg *et al.*, 2002). In the present study (Paper **IV**), a coupled C and N mineralization study was not made, though it may have been an advantage and should, therefore, be considered in future investigation.

Finally, for the smallholder farmer, the longevity of improvements to soil quality may not be of an immediate concern. The bottom-line is that the organic material has proven efficacy in boosting crop production in the short-term, and the species selected should preferably provide multiple benefits. Once, the benefits are recognized by more farmers, there would be a high propensity for inclusion of more woody biomass in the landscape, and consequently for an increased C-sequestration in soil and plant biomass, increased fodder, wood, food supply and increased soil quality in the long term. Such increase in woody biomass would obviously mean that more green manure (and litter) can be obtained for use as farm inputs. As from the present study (Paper **V**), application of ≤ 3 Mg ha^{-1} green manure input from locally available species with high P content (e.g. *Croton* and *Cordia*) in combination with inorganic fertilizers might provide a modest increase in first-season crop yield, but this has to be evaluated from the practical and economic point of view as well. In addition, when organic materials from legumes with high N content but also high polyphenols content (*e.g. Albizia* and *Milletia*) have to be used, they should constitute only a smaller proportion of the GM-fertiliser mixture. However, as the study was a short-term one (*i.e.* two years), studies over a longer period of time which also explore alternative ways of utilising the GM (*e.g.* composting) should be considered.

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