ABSTRACT

MCCLINTOCK, NATHAN CRANE. Production and Use of Compost and Vermicompost in Sustainable Farming Systems. (Under the direction of Noah Nathan Ranells.)

Compost use in agriculture has gained popularity in recent decades as public concern over the environmental impact of synthetic inputs in agriculture has increased. Compost application has been associated with improvements to soil physical and chemical properties. Thesis research focused on compost production and utilization in an organic farming system in North Carolina and in a smallholder subsistence farming system in semi-arid West Africa.

Part 1: An experiment was conducted at the Center for Environmental Farming Systems (CEFS) in Goldsboro, NC, to compare methods of composting separated solid swine waste and various rates of wheat straw. Straw was chopped (<10 cm) or unchopped and mixed with manure at five different rates and placed in piles ($1m^3$) for composting. Sub-samples of each mixture were stocked with earthworms (*Eisenia fetida*) for vermicomposting. After 3 weeks, additional sub-samples were removed from piles and stocked with worms. At Weeks 3, 6, and 10, chop significantly affected C and N concentrations and C:N ratios in both vermicomposting treatments, generally in high-straw mixtures. By Week 13, chop was no longer significant. Overall, worms were not able to degrade straw fractions of mixtures that were not pre-composted.

Part 2: An experiment was conducted at a site in the North Carolina Piedmont (Pittsboro) and another in the Coastal Plain (Goldsboro) to evaluate the integration of compost with cover crops, both common sources of fertility in organic farming systems. Treatments were: poultry litter compost (COMP), crimson clover (CLOV), clover + compost (MIX), and a control fertilized with soymeal (SOY). COMP and CLOV plots were also amended with soymeal to equalize N rates across treatments. Treatment differences did not affect sweet corn height at 5 or 7 weeks after planting (WAP) or biomass (DM) accumulation at 5 WAP at either site. At Goldsboro, CLOV yielded 22% more DM at harvest than COMP and 31% more marketable ears. Total yield of COMP plots was 22% less than CLOV while marketable yield was 20 to 31% less than CLOV, MIX, or SOY treatments. Release of plant available nitrogen (PAN)

from decomposing clover (C:N 11.1) may have been slower than from compost (C:N 8.1) or soymeal (C:N 6.2), coinciding with the period of maximum uptake by corn plants. Soil inorganic N (SIN) concentration was greater at Pittsboro, likely due to method of incorporation (roto-tilled vs. disked) and soil type. In a lab incubation of both soils (and which did not include soymeal), SIN in Goldsboro MIX treatments was greater than the sum of CLOV and COMP SIN, suggesting a priming effect, likely masked by soymeal in the field experiment.

Part 3: The *Jóór* (Dior) soils of Senegal's Peanut Basin are inherently low in OM, limiting yields of millet and other crops and threatening the food security of smallholders. A series of focus groups and interviews were conducted in eight villages to characterize the site-specific fertility management practiced by farmers in the Peanut Basin. On-site measurements revealed little significant difference between the effects of compost and manure on peanut and millet growth, but significant increases over unamended areas. Similarly, chemical analysis revealed increased cation exchange capacity and nutrient concentrations in soils amended with compost or manure. Similarities in the chemical characteristics of compost and traditional pile manure (*sëntaare*) suggest that development workers could emphasize improved pile management rather than promoting more labor-intensive composting.

PRODUCTION AND USE OF COMPOST AND VERMICOMPOST IN SUSTAINABLE FARMING SYSTEMS

by

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Co-chair of Advisory Committee - Co-chair of Advisory Committee

For my grandmother Mildred Clough (1916 – 1997),
for my father David McClintock (1932 – 1989),
and for the landscapes they loved.

Biography

After his first several months *in utero* in Amman, Jordan, Nathan Crane McClintock was born in Washington, DC, on July 2, 1974, to Susan Clough Wyatt and David Wm. McClintock. His interest in agroecology was cultivated at an early age as his family reclaimed a pre-Civil War farm from the brambles of Rappahannock County, Virginia, and by visits to his great-grandparents' homestead in the wheat fields of Quay County, New Mexico. In 1984 Mr. McClintock moved with his family to Raleigh, North Carolina. He later attended the University of North Carolina at Chapel Hill and l'Université Jean Moulin in Lyon, France, where he studied French, folklore, and creative writing. After completing his B.A. in 1996, he traveled and studied in Mexico and Central America, before heading north to milk goats and farm on Pender Island, British Columbia, later traveling and working in Alaska and Asia.

Mr. McClintock served as a Peace Corps agricultural extension volunteer in a small village in the Sikasso region of Mali, West Africa, from 1998 to 2000, working with local farmers and women's groups to improve food and nutrition security. Following his service, Mr. McClintock returned to North Carolina to manage an organic farm near Pittsboro. He completed a Certificate of Farm Stewardship from the Sustainable Farming Program at Central Carolina Community College (CCCC) in 2001 prior to beginning his M.S. at North Carolina State University. In addition to conducting fieldwork at CCCC in Chatham County and at the Center for Environmental Farming Systems in Goldsboro, his research in composting took him back to West Africa, where he interned as a researcher at the Rodale Institute in Senegal. He writes, teaches, and gardens in Pittsboro, and intends to continue working for the promotion and development of local and sustainable food systems at home and overseas. He speaks French, Spanish, Bambara, Wolof, and Haitian Creole and hopes to continue learning.

Acknowledgements

Bamananw ko bolodenni kèlèn tè bèlè ta. The Bambara say that one little finger cannot pick up a stone. This ancient Malian adage seems the most appropriate and gracious way to sum up the communal spirit surrounding my thesis work during its many incarnations.

First, I am grateful to my committee members for their guidance throughout my program. To my advisor and fellow *subvercionista* Dr. Noah Ranells, my utmost thanks and appreciation for his support throughout my often roundabout course of study, for his willingness in allowing me to take the helm, and for his editorial vigor. I am indebted to Dr. Nancy Creamer for being the gentle and reassuring voice of reason throughout this program. Many thanks go to Dr. Paul Mueller for his help with the fine-tuning as I brought this all together, and to Dr. Frank Louws for his insightful input, and the wisdom that self-worth is not derived from one's data set.

The vermicomposting experiment would not have been possible without the guidance and logistical support of the following: Center for Environmental Farming Systems (CEFS) Superintendent Eddie Pitzer, Rhonda Sherman-Huntoon, Dr. Jean-Marie Luginbuhl and Amy Conrad at the Goat Unit, Sharon Freeman, Mike Regans of Greene County Cooperative Extension, Todd Balance at White Oak Farm, and the staff at the Lake Wheeler shop.

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Finally, to the people of Dialakoroba, Mali, whose resilience, sweat, and spirit provided me the original inspiration for this journey: *Aw ni cè, aw ni baaraji, Ala k'aw kisi. Ala k'an tò nyògòn ye.*

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List of Abbreviations

ACDK	*Association Communautaire pour le Développement de Koumpentoum*, Koupentoum Community Development Association
Al	aluminum
ANOVA	analysis of variance
B	boron
Ca	calcium
CAFO	confined animal feedlot operation
Cd	cadmium
CEC	cation exchange capacity, measured in cmol kg^{-1} at buffer pH
CFU	colony forming unit (bacterial count)
C:N	carbon-to-nitrogen ratio
CO_2	carbon
CRAR	*Centre de Ressource pour une Agriculture Régénératrice*, Rodale Institute's Regenerative Agriculture resource Center in Thiès, Senegal
Cu	copper
CV	coefficient of variance
Db	bulk density
DM	dry matter
EC	electrical conductivity
ECEC	effective cation exchange capactiy (CEC at soil pH)
F CFA	West African franc (*franc Communauté Financière Africaine*), 656 F CFA = 1 euro = ~ $1
Fe	iron
GIE	*Groupement d'interêt économique*, Senegalese rural cooperatives
HUE	harvest use efficiency (HUE = total N of plant at maturity / total N applied × 100)
ISRA	*Institut Sénégalais de Recherches Agricoles*, Senegalese Agricultural Research Institute
K	potassium
LDFE	liters of diesel fuel equivalent
LSD	least significant difference
LS MEANS	least significant means
Mg	magnesium
MM	Metro-Mix
Mn	manganese
Mo	molybdenum
MSW	municipal solid waste
N	nitrogen
Na	sodium
NCDA & CS	North Carolina Department of Agriculture & Consumer Services
NGO	non-governmental organization
NH_3^+	ammonia
NH_4^+	ammonium
NO_2^-	nitrite
NO_3^-	nitrate
NRBAR	Natural Resource and Basic Agricultural Research fund (USAID)
O_2	oxygen
OM	organic matter
P	phosphorus
$P_2O_5^-$	phosphate
PAONG	*Projet d'Appui des Organisations Non-Gouvernmentales*, NGO Suppport Project (USAID-funded)
PAN	plant available nitrogen
Pb	lead
PROGES	*Projet de Gestion des Eaux de Casamance*, Casamance Water Management Program

List of Abbreviations (cont'd)

RA	regenerative agriculture
Rodale	The Rodale Institute
RP	rock phosphate
SAP	structural adjustment program
SIN	soil inorganic nitrogen (SIN = $NO_3^- + NH_4^+$)
SOM	soil organic matter
TKN	total Kjedahl nitrogen
TS	total solids
UGIED	*Union des Groupements d'Interêt Economique du Delta*, Delta Rural Cooperatives' Union
USAID	United States Agency for International Development
VS	volatile solids
WAP	weeks after planting
WHC	water-holding capacity
Zn	zinc

SI units:

µm	micrometer (1µm = 1×10^{-6} m)
cmol kg^{-1}	centimole of charge per kilogram, a measure of CEC and ECEC
g	gram
Gg	gigagram (1 Gg = 1×10^{9} g)
ha	hectare (1 ha = 1×10^{4} m^2)
km	kilometer (1 km = 1×10^{3} m)
kg	kilogram (1 kg = 1×10^{3} g)
L	liter
mg	milligram (1 mg = 1×10^{-3} g)
Mg	megagram, metric ton (1 Mg = 1×10^{6} g)
mL	milliliter (1 mL = 1×10^{-3} L)

Chapter 1: Composting and the post-Green Revolution paradigm of sustainable soil fertility management

Following the Second World War, the "Green Revolution" transformed the nature of agriculture worldwide. The logic was simple: increase production to feed a growing world population. In an effort to avert famine of Malthusian[1] proportions, agronomists and policy-makers promoted a combination of chemical fertilizer inputs and newly hybridized short-stature or dwarf cultivars throughout the industrialized and developing world. The impact was enormous, as crop yields increased to levels previously deemed impossible (Pretty, 1995; Conway and Barbier, 1990). The Green Revolution resulted in production increases of 2.1% per year between 1950 and 1990, leading to a tripling of world food production during the same period (Manning, 2000).

While largely lauded as the key to averting famine in the developing world, the success of Green Revolution technology became more and more dependent on off-farm inputs. Due to high input costs, large acreages of crop monocultures were necessary to make annual production profitable. While this facilitated mechanical planting, fertilization, and harvest, the loss of diversity increased insect, weed, and pathogen pressure (Conway, 1997; Ascher and Healy, 1990; Conway and Barbier, 1990). Organic matter cycling was de-emphasized under this production-centric paradigm, and as a result, natural soil fertility declined and yields became contingent on increased inputs (Chopra and Rao, 1997; Altieri, 1999). In the United States and the rest of the industrialized world, the 1962 publication of Rachel Carson's *Silent Spring* brought the dangers of pesticides such as DDT to the public's attention, helping motivate a movement to seek and promote new alternative agriculture paradigms (Kroese, 2002; Sligh, 2002).

Nevertheless, fertilizer use has increased more than four-fold worldwide since 1961, peaking at 145.2 million Mg in 1988 (FAOSTAT) [Figure 1.1]. This increase has been more dramatic in developing countries, from 3.7 million Mg in 1961 to 86.7 million Mg in 2001. Green Revolution technology was offered to developing countries in the form of humanitarian aid packages and later heavily subsidized by recipient governments to make

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[1] In 1798 Thomas Malthus argued that population growth always exceeds food production, and that starvation and disease are "positive checks" to a rising world population He added that any effort to increase production would simply result in increased growth, thereby amplifying the cycle of growth and starvation (Malthus, 1836).

them affordable to farmers (Conway, 1997). In some cases, these subsidies led to the excessive or improper use of Green Technology inputs, ultimately resulting in intensified resource degradation (Barbier, 1997).

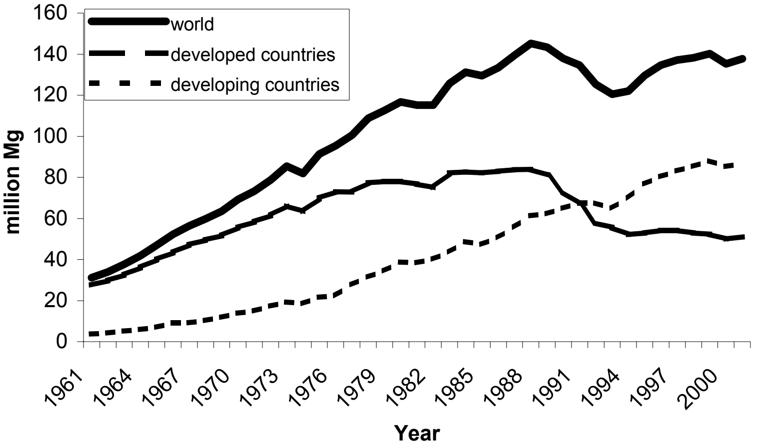

Figure 1.1: Fertilizer consumption worldwide, in developed countries, and in developing countries (source data: FAOSTAT)

The global expansion of neo-liberal macroeconomic policy, or "free trade," over the last decade has also had a profound effect on agriculture in developing countries. While some argue that structural adjustment policies (SAPs) may lead to more responsible resource management (Senehoun *et al*. 1999; Barbier, 1997), others argue that they have an immediate negative impact on the food security of poor farmers, as agricultural subsidies are phased out and markets are opened to industrial agriculture competitors (Mittal, 2002; Rosset, 2001). The importation of subsidized US and European grain has left farmers little choice but to shift from growing devalued food crops to specialized cash crops for export. Many of these are not food crops, and unlike traditional crops, their by-products or residues are rarely multi-purpose. With fluctuations in the global market, developing country farmers often default on loans taken for the purchase of inputs (Mittal, 2002; Rosset, 2001).

Additionally, population growth in these regions and consequent rural-to-rural and rural-to-urban migration has led to more intensive cropping patterns on ecologically marginal lands and in urban peripheries; the resulting nutrient mining has depleted soils in many parts of the developing world (Wezel and Rath, 2002; Dreschel et al, 1999; Chopra and Rao, 1997). Since 1990, world grain production has slowed to an annual increase of 0.5%, a much lower rate than during the first decades of the Green Revolution (Manning, 2000). While population rates decrease in the industrialized world, they remain high in many parts of the developing world, often in the same marginal environments where Green Revolution technology performs poorly. In many parts of sub-Saharan Africa, for example, population growth exceeds 3%, while per capita food production is declining (FAOSTAT; Conway and Barbier, 1990).

Clearly, the need for a regenerative approach to soil fertility and resource management is critical, not only to reduce dependence on costly inputs that may compromise ecological integrity, but also to buffer against environmental and economic instabilities that threaten food security and food sovereignty for small farmers. Altieri (1995) expands upon this notion:

> "[…] The modern approach is no longer appropriate in an environmentally-troubled and energy-poor era; […] progress toward a self-sustaining, resource-conserving, energy-efficient, economically viable and socially acceptable agriculture is warranted."

As agroecosystems are threatened by degradation and a loss of diversity, it may become necessary to adopt a conservation approach to managing farming systems in order to limit potential losses and cycle limiting resources. Liebig's Law of the Minimum states that production is limited by the scarcest resource (van der Ploeg *et al.*, 1999), a metaphoric leaky barrel with staves of differing lengths. As the shortest is replaced, the barrel continues to leak from the next shortest stave. Through the strategic cycling of nutrients and organic matter (OM) back into the system, farmers may be able to mitigate some of these limiting factors.

Organic waste has been used for millennia as a source of fertility. Application of decomposed manures and other composted organic material was common in the ancient civilizations of the Mediterranean region, India, China, and Japan (Howard, 1943; Epstein, 1997). In the developing world where the high costs and scarcity limit fertilizer use, it remains a primary source of fertility for many small farmers in the (Diop, 1999; Pretty, 1995). Louden's 1839 *Encyclopedia of Gardening* included the recipes for composting several organic wastes suitable for optimum plant growth (Raviv *et al.*, 1986). An 1888 Bulletin of the North Carolina Agricultural Experiment Station featured "Composts—Formulas, Analyses, and Values" (Epstein, 1997). The modern system of aerobic, thermophilic composting is generally attributed to Sir Albert Howard, who brought the Indore process to the world's attention in a 1931 publication. The technique, named for the state in central India where it was developed from 1924 to 1931, resulted from Howard's frustrations with the growing incidence of plant disease and a loss of humus in the monocultures of Western agriculture and from his observation that "the Chinese have maintained soil fertility on small holdings for forty centuries" (Howard, 1943). In his memoir *An Agricultural Testament*, the prosaic Howard bemoans the unfilled potential in the West of returning waste to the soil:

> Can anything be done at this late hour by way of reform? Can Mother Nature secure even a partial restitution of her manurial rights? If the easiest road is first taken, a great deal can be accomplished in a few years. The problem of getting the town wastes back into the land is not difficult. The task of demonstrating a working alternative to water-borne sewage and getting it adopted in practice is, however, stupendous.

He noted, however, that traditional methods of piling manure before application was inefficient: "The fungi and bacteria of the manure heap are working under impossible conditions. They live a life of constant frustration which can only be avoided by giving them a balanced ration." He experimented with several systems and concluded that pits or piles, depending on availability of labor and rainfall, were optimal for composting vegetable wastes with a carbon-to-nitrogen ratio (C:N) less than 33:1 with manure, urine, and slaughterhouse by-products. Waste was layered to promote aeration, moistened via irrigation or rainfall, and turned after 2 or 3 weeks. He noted an initial temperature of 65°C that declined to 30°C after 90 days. Following publication, the Indore process was widely adopted on coffee and tea plantations throughout the British colonies in Asia, Africa, and the Caribbean (Howard, 1943).

Today, organic farmers in industrialized nations and practitioners of sustainable agriculture worldwide rely heavily on compost as a means of cycling organic matter (OM) back into the soil, improving soil physical and chemical properties, mitigating soil-borne pathogens, and managing organic waste. Due to pressing concerns about local watershed pollution and on-site nutrient loading, many large-scale livestock producers are exploring composting as a means of managing manure while creating a value-added product for sale. Municipalities have begun to rely heavily on composting as a waste stream management system that diverts yard and pruning waste from precious landfill space. As tipping/dumping fees and public scrutiny increase, industries have turned to composting as an economically viable way to dispose of processing wastes such as brewery and papermill sludge, slaughterhouse refuse, newspaper, cardboard, and food processing residuals. Considerable research has focused on composting municipal sewage sludge, also known as "biosolids" or "night soil," used in China as a fertilizer for centuries.

Nevertheless, compost production and use is no panacea for agriculture, industry, or government. Indeed, the use of composted industrial and municipal wastes in agricultural production—particularly sewage sludge—has caused public alarm as ethical, public health, and environmental concerns are voiced. Antibiotics, lethal human pathogens such as *E.coli* and *Salmonella*, antibiotics, heavy metals, or other toxins may be transferred from applied waste to food harm farmworkers during application (Garrec et al., 2003; National Academy of Sciences, 2002; Jones, 1999). Excessive use on fields may lead to high concentrations of some nutrients and metals (Kpomblekou *et al*., 2000; Eghball and Gilley, 1999; Gigliotti *et al*., 1996), harming crops, consumers, and the watershed. Compost production, transportation, and application costs may not be economically feasible for large-scale farmers transitioning to sustainable methods (Reider *et al*. 1991). Others view compost use as creating dependency on costly off-farm inputs. A lack of compost quality standards may place farmers at risk of importing weed seed, pathogens, and garbage. While some of these issues lie outside the scope of this thesis, they are central to any debate on compost's role in the creation of sustainable farming systems to ensure food security and responsible land stewardship throughout the world.

Chapter 2: Production and utilization of compost and vermicompost in sustainable farming systems—A review of the literature

2.1. Introduction

In the past decade, researchers have focused considerable attention on the production and use of compost on several levels, including but not limited to agricultural, industrial and municipal waste management, soil amendment and fertility, nutrient cycling, carbon sequestration, bioremediation, erosion control, and environmental quality. While the contribution of composting literature to each of these areas of interest is vast, the scope of this literature review is limited to a general overview of vermicomposting and aerobic, thermophilic composting, and the agricultural utilizations of both forms of compost. The review concludes with a brief analysis of the economics of both composting technologies.

This presentation of the composting process and the agroecological effects of compost application on farming systems worldwide is intended to stimulate further discussion and research on the potential role of compost production and utilization in promoting sustainability in a diversity of agricultural systems.

2.2. An overview of thermophilic composting

2.2.1. General mechanics of composting

The breakdown of organic matter during the composting process is dependent on several factors working in concert. These include moisture, microbial populations, oxygen (O_2), and a balance of carbon (C) and nitrogen (N) [Figure 2.1]. Microorganisms in the organic matter (OM) consume the readily available C. As it is metabolized, temperatures increase in the compost pile and carbon dioxide (CO_2) is released. As a result, the pile is newly populated with thermophilic, or heat-loving, bacteria that consume the rest of the degradable C. As microbial activity slows, temperature decreases, allowing for colonization by fungi that slowly consume much of the remaining recalcitrant forms of C—lignins and cellulose. The resulting crumbly, earthy humus is considerably more stable than manure, meaning that its nutrients are less likely to be lost to leaching or volatilization into the atmosphere. As compost matures, its nitrogen is mineralized, moving from its organic form to ammonium and then nitrate, the preferred form for plant uptake.

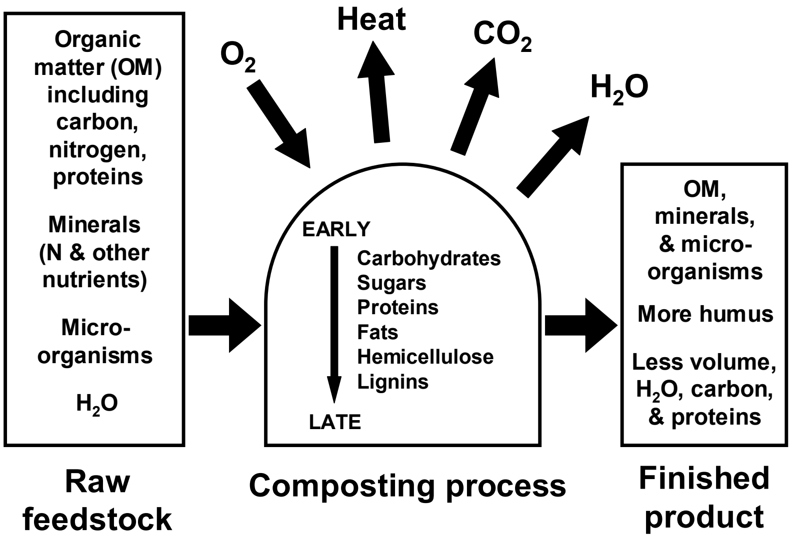

Figure 2.1: Schematic diagram of the mechanics of thermophilic composting (adapted from Epstein, 1997, and NRAES, 1999)

2.2.2. Aeration, moisture, and temperature

Continued metabolism depends on sufficient aeration. Average O_2 concentration inside the compost mix is 15 to 20%, while CO_2 is 0.5 to 5%. When O_2 content falls below these levels, anaerobic microbial populations surpass aerobic species. As a result, malodorous fatty acids and methane levels may increase (Druilhe *et al*. 2002). Because oxygen consumption is a function of microbial activity, oxygen levels are also related to substrate temperatures. Temperatures between 28 and 55°C are optimal; few species of bacteria can survive at temperatures above 70°C. Fungi capable of degrading cellulose and lignin are also greatly inhibited by high temperatures (de Bertoldi *et al*., 1984). The US Environmental Protection Agency mandates adherence to a "process to further reduce pathogens" (PFRP), as described in US-EPA's 40 CFR Part 503, for a compost to be classed as Class A for commercial distribution. Substrates must reach 55°C for three consecutive days or more, or temperature of the coolest part of the compost must remain at 55°C for at least three consecutive days (Ndegwa and Thompson, 2001).

2.2.3. Carbon and nitrogen dynamics

During the first day or two of aerobic composting, labile OM carbon is initially degraded by bacterial enzymes present in mesophilic microflora flourishing at temperatures between 90 and 110°F (50 to 61.2°C). As microbial metabolism of readily soluble carbohydrates in the compost feedstock increases, more oxygen is consumed and carbon dioxide released, raising temperatures as high as 70°C and leading to increases of thermophilic, or heat-loving, microbial populations (Epstein, 1997; Eiland *et al.*, 2001; Druilhe *et al.*, 2002). This stage, called the thermophilic stage or active composting, generally lasts a month to six weeks, and is the period during which the majority of readily degradable C is consumed. Once labile C is degraded, microbial activity slows and temperature drops; the majority of the remaining carbon is in the form of lignin or cellulose. Because lignin is the carbon compound that is most recalcitrant to degradation, substrates with high lignin content are not quickly composted (Vincelas-Akpa and Loquet, 1997). Eiland *et al*. (2001) noted that total C concentrations remained constant during the initial mesophilic phase until temperatures peaked 70°C in a mixture of pig (*Sus scrofa domesticus*) manure and miscanthus (*Miscanthus* spp.) straw, decreasing over 10 to 50 days from 40 to 69% of initial levels. Lignin fractions were not degraded by composting periods of 65 and 70 days. Hemicellulose concentrations, on the other hand were reduced to 6% of initial levels over the composting period. In contrast, cellulose concentrations remained constant until day 8, then decreased and stabilized by day 50 at 30 to 36% of initial levels. Both cellulose and hemicellulose fractions remained constant during the first week of thermophilic composting until soluble C was metabolized by microbes.

Nitrogen dynamics during composting are largely related to microbial activity. Most N in composting substrate is in the organic form, mostly as proteins and simple peptides. During the initial rise in temperature, heterotrophic microbes attack the amine groups present in organic matter as humus or proteins, forming amino compounds. Following hydrolization, N is either released as ammonium (NH_4^+) or is immobilized by other microorganisms and returned to its organic form (Brady and Weil, 2002). When substrate temperatures exceed 40°C or if pH rises above 7.5, N generally volatilizes as ammonia (NH_3^+). Nitrate (NO_3^-) concentrations in the compost substrate are low during this thermophilic phase due to O_2 consumption by the nitrifiers. During mineralization, hydrogen ions are consumed or lost as water, thereby lowering the pH of the substrate. When temperatures drop below 40°C, chemoautotrophic bacteria (*Nitrosomonas* spp.) transform ammonium to nitrite (NO_2^-):

$$2NH_4^+ + 3O_2 \rightarrow 2NO_2^- + 4H^+ + 2H_2O$$

As substrate temperature drops following the consumption of soluble C by heterotrophic microorganisms, O_2 concentrations in the substrate increase due to the lack of C available for further consumption, leading to increases in *Nitrobacter* spp. activity that transforms nitrite to nitrate (Bernal *et al*., 1998b; Eiland *et al*., 2001):

$$2NO_2^- + O_2 \rightarrow 2NO_3^-$$

Mineralization of organic N slows in the latter phases of composting as remaining ammonium is consumed, resulting in increases of nitrate concentrations (Sánchez-Monedero *et al*, 2001).

In a study of four compost mixtures—sewage sludge + cotton (*Gossypium hirsutum*) waste, sorghum (*Sorghum bicolor*) bagasse + pine (*Pinus* spp.) bark + urea, sorghum bagasse + pine bark + brewery sludge, and municipal solid waste (MSW) + sorghum bagasse—the highest ammonium concentrations occurred during the first weeks as OM degraded and mineralizing organic N produced ammonium. Ammonium concentrations decreased after the first 2 to 3 weeks during the thermophilic phase and eventually reached 4 mg g^{-1} when temperatures stabilized at 42 to 77 days. Organic N mineralization was minimal at this time as little ammonium was available to nitrifying bacteria. As ammonia was solubilized as ammonium, pH increased from 7.6 and 6.8 to 8.2.Nevertheless, high ammonia losses were reported in the MSW compost due to an extended thermophilic phase and the lack of a carbonaceous bulking agent (Sánchez-Monedero *et al*, 2001). In another experiment using a sorghum bagasse + sewage sludge compost and a bagasse + pig (*Sus scrofa domesticus*) slurry + poultry manure compost, losses of ammonia to volatilization were low due to a $pH < 7$ and low temperatures (< 55ºC) (Bernal *et al.*, 1998b). Eiland *et al.* (2001) reported constant total N concentrations until temperatures peaked 70°C, then decreased gradually to 20°C. Nitrate concentrations decreased during the thermophilic and early cooling phases before rising until the experiment concluded.

2.2.4. Indices of compost stability and maturity

According to Bernal *et al.* (1998b) maturity and stability of compost imply the absence of phytotoxic compounds and plant or animal pathogens. More specifically, they cite stability as generally related to microbial activity, whereas maturity is more associated with the absence of phytotoxins. Microbial activity is widely accepted as the most reliable indicator of compost stability and several studies have attempted to correlate various physical and chemical parameters to respiration (Bernal et al., 1998b; Belete et al., 2001; Eggen and Vethe, 2001; Brewer and Sullivan, 2002). Microbial respiration, as measured by O_2 uptake and CO_2 production, generally decreases with the loss of readily biodegradable carbon and the subsequent stabilization of the remaining fractions (Brewer and Sullivan, 2002). Brewer and Sullivan (2002) reported high respiration rates during the first 27 days of aerated yard waste compost, and stable respiration during the curing period of 70 to 133 days. Microbial biomass is another measure of stability (Bernal et al., 1998b). Belete *et al*. (2001) estimated microbial populations not only by respiration, but also by measuring colony forming units (CFUs) and cell counts using epiflourescence microscopy. In a forced-aeration windrow of household and yard waste compost bulked with wood chips, they found a significant correlation between compost age and decrease in microbial CFUs, respiration, and bacterial cell counts.

Water-soluble organic carbon generally decreases with time and is often used as another indicator of compost stability (Bernal et al., 1998b; Belete et al., 2001; Eggen and Vethe, 2001). In a paper mill sludge compost, a fish waste compost, and two biosolids composts, Eggen and Vethe (2001) found that water soluble total organic C was the only parameter significantly correlated with respiration (r^2=.82). With the two biosolids composts, the correlation was quite strong (r^2=.995). Similarly Bernal et al. (1998b) reported reductions in water soluble organic C in various mixtures of sewage, MSW, pig slurry, crop residues, and olive (*Olea europaea*) mill wastewater, and attributed the decreased C to the rapid degradation of sugars, amino acids, and peptides. Eggen and Vethe (2001) also correlated total organic carbon in the fulvic fraction to microbial respiration. As compost stabilizes, the ratio of humic to fulvic acids (humification) increases, due to loss of readily degraded fulvic acids (Bernal *et al*., 1998b). Cation exchange capacity (CEC) increases as a result of the increase in the humic fraction of the compost (Vincelas-Akpa and Loquet, 1997; Tomati *et* *al*., 2000). Bernal *et al*. (1998b) reported rapid increases in CEC from initial levels between 36.4 and 119.9 cmol kg^{-1} to levels of 95.1 and 236.3 cmol kg^{-1}. While many researchers have noted increases in humification and CEC, these often do not correlate with respiration (Eggen and Vethe, 2001; Brewer and Sullivan, 2002).

Equally difficult to correlate with compost maturity is the reduction in the carbon to nitrogen (C:N) ratio. C:N is measured either in a solid compost or a compost water extract. The N concentration in mature compost is generally very low and the C:N in compost is generally higher in the solid compost than in the water extract (Bernal *et* al., 1998b; Eggen and Vethe, 2001). Other research has correlated C:N with other stability indices (Bernal *et al*., 1998a; Bernal *et al*., 1998b; Eiland *et al*., 2001). While the C:N ratio will vary depending on the compost feedstock, C:N ratios less than 12 are often considered stable (Bernal *et* al., 1998b).

Nitrification is another measure of compost maturity. Since temperatures greater than 40º C inhibits nitrifiers, nitrification generally occurs after the thermophilic phase. Mineralization of organic N is limited during the final phases of composting when little ammonium is available to bacteria (Sánchez-Monedero *et al.*, 2001). As phytotoxic NH_4^+ concentrations decrease and NO_3^- concentration increases, the compost is considered mature (Bernal *et al.*, 1998b; Eiland *et al*., 2001).

2.3. Thermophilic composting systems

As Sir Albert Howard noted in the first half of the 20th century, farmers have relied on decomposed animal manure to increase soil productivity for millennia. While the manure in a pile does decompose after a year or more, much of the decomposition is likely anaerobic, leading to loss of N as ammonia and foul-smelling emissions of methane and hydrogen sufide. If bedding is included in the manure or if the manure is relatively dry, then conditions may be adequate for aerobic decomposition. As previously discussed, sufficient oxygen must be present in the substrate to allow for the colonization of aerobic, thermophilic bacteria. If adequate aeration and carbonaceous materials are available to prevent significant amounts of ammonification, successful thermophilic composting of the substrate may occur. This is known as passive composting (NRAES, 1992). Such ideal conditions are rare, however.

The original Indore method proposed by Howard (1943) involved layering of carbonaceous and nitrogenous residues to facilitate aeration and homogenize feedstock mixtures. “Pit composting” was described as a method that places organic wastes in a below-ground depression or pit to reduce moisture loss. Howard recommended this method for semi-arid areas with limited water availability. The pit is often lined with cement or cement blocks, and is often at least 2 to 3 m long, 1 to 1.5 m wide and 1 to 1.5 m deep. In areas where water is readily available, Howard recommended composting in aboveground piles. This is less labor-intensive because it does not require the labor of pit construction.

Small compost piles may be turned manually with a pitchfork to aerate. In industrialized countries, farms may rely on tractors with front-end or bucket loaders to turn the compost. Most large on-farm and commercial composting facilities use either a turned windrow system, passively aerated windrows, or aerated static piles.

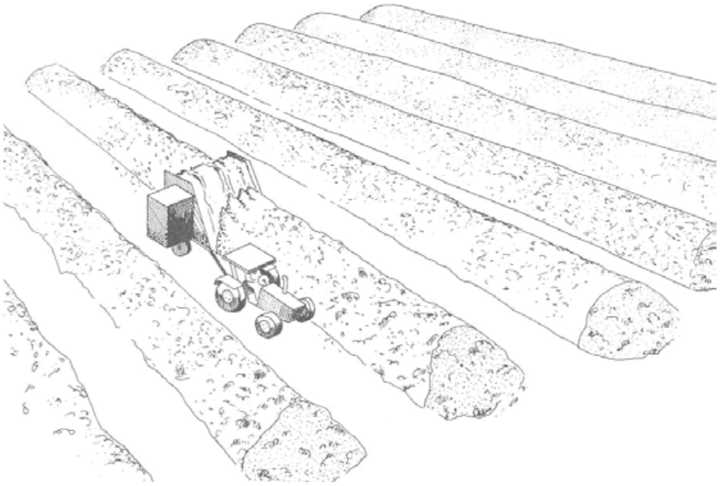

Figure 2.2: Windrows composting with tractor-powered aeration (source: *On-Farm Composting Handbook,* NRAES-54, 1992)

2.3.1. Windrow composting

In large-scale windrow composting, manure or other feedstock is mixed and shaped into long, narrow piles called windrows. These are generally 3 to 6 m wide and 3 to 4 m tall and turned either with a bucket loader or a PTO-driven compost turner that is pulled slowly through the length of the windrow [Figure 2.2]. Windrow size depends on the density of the feedstock material; windrows of dense manures with smaller pore space need to be smaller than windrows of feedstocks with larger particle sizes such as yard waste. As particle size increases, aeration improves. Both initial mixing and frequent turning allow for uniform distribution of substrate of varying particle size, thus reducing the potential for pockets of anaerobic decomposition in areas that are too moist or too rich in nitrogenous substrate. Additionally, repeated aeration "fluffs up" the compost material, increasing pore space around individual particles, thus maximizing oxygen availability to active microbial populations. Hot gases and water vapor accumulating at the center of the windrow are released at each turning and feedstock on the exterior is moved to the core where it can experience elevated temperatures (NRAES, 1992). In a comparison of turned and unturned windrows of hoop house manure (pig manure + corn [*Zea mays*] stalks), Tiquia *et al*. (2002) observed a faster rate of composting in turned windrows, leading to greater C, potassium (K), and sodium (Na) losses. Turning did not affect N loss, which ranged from 37 to 60 %.

2.3.2. Static pile composting

Passively aerated windrows receive oxygen through perforated pipes places through the base of the compost. Oxygen enters the substrate through the exposed open ends of the pipes [Figure 2.3]. Windrow height of 1 m allows air penetration to prevent pockets of anaerobic activity. Since the windrow is not turned, feedstock must be well-mixed prior to placement in the windrow. Material is placed on an absorbent layer of mature compost, straw or peat to absorb moisture. The NRAES's *On-Farm Composting Handbook* notes that this method is used in Canada to compost seafood waste and peat, and manures with wood chips or straw in eight to twelve weeks (NRAES, 1992). Sartaj *et al*. (1997) found that passive aeration resulted in faster composting of poultry manure and peat than forced-air aeration and turned windrows.

In forced-aeration static pile composting [Figure 2.4], air is pumped or drawn through ventilation pipes placed underneath the compost feedstock. Electric blowers or pumps can be controlled by timers or thermostats. With a thermostat, the fans are activated when the compost attains a certain temperature. With the timer system, the fans are activated for a specified duration at regular intervals. De Bertoldi *et al*. (1984) noted that pile height needed to be limited to 3 m to allow oxygen emitted from below to infiltrate upper levels of the substrate, while NRAES (1992) recommended that short windrows not exceed a height of 2.4

m. In a forced aeration system, producers can control composting conditions such as moisture, temperature, and aeration, with much greater precision than in other systems. De Bertoldi *et al*. (1984) found that airflow of 0.2 $m^3 min^{-1} Mg^{-1}$ was sufficient to provide an oxygen concentration of 15 % in a substrate of wood chips and sludge. Forced aeration can compost material in three to five weeks (NRAES, 1992). Nevertheless, Sartaj *et al*. (1997) found that forced aeration of windrows resulted in greater N loss than passive aeration. Additionally, it could not maintain temperatures > 50ºC as long as passively aerated windrows.

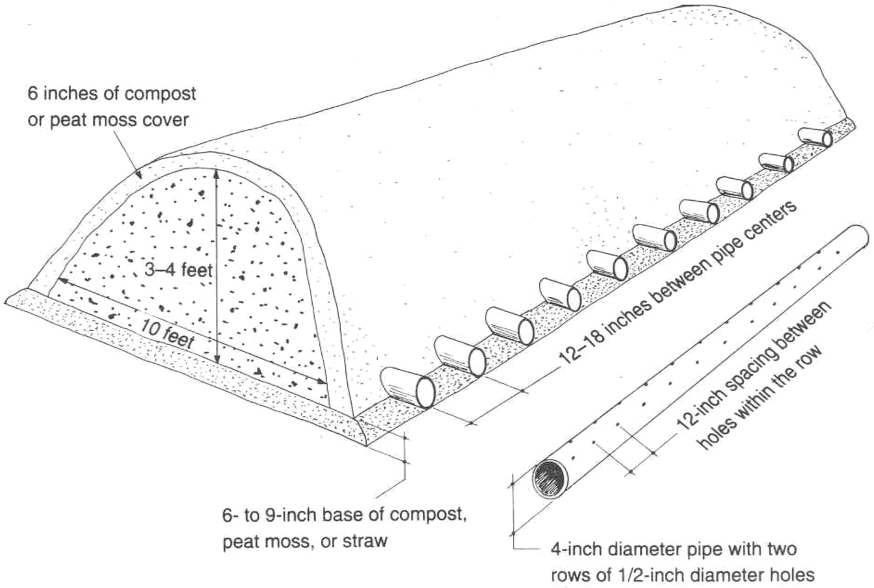

Figure 2.3: Passive aeration static windrows (source: *On-Farm Composting Handbook,* NRAES-54, 1992)

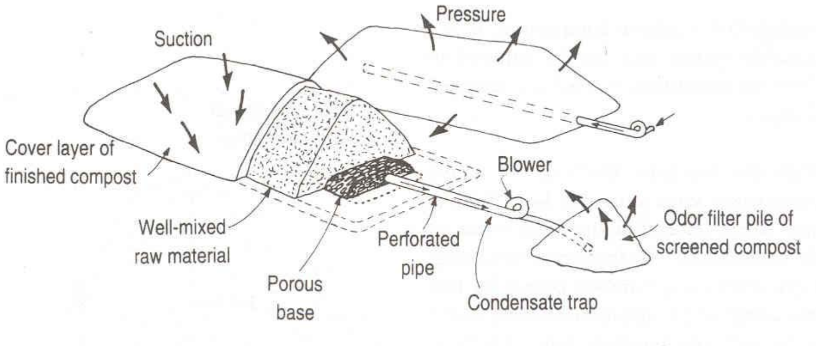

Figure 2.4: Forced aeration static windrows (source: *On-Farm Composting Handbook,* NRAES-54, 1992, adapted from Wilson, *Manual for Composting Sewage Sludge by the Aerated Pile Method*)

2.4. An overview of vermicomposting

2.4.1. Development of vermicomposting worldwide

Humankind has long-recognized the ability of the earthworm (Lumbricidae) to transform organic waste into humus-rich material with soil fertilizing capabilities; indeed, Aristotle referred to earthworms as the “intestines of the earth” (Kale, 1993). Charles Darwin’s 1881 treatise *The formation of vegetable mould through the action of worms with observations on their habits* is widely regarded as the first modern scientific study of the beneficial role in of earthworms and their castings in the soil ecology (Bouché, 1987). Bouché traces the birth of vermiculture, the production of earthworms, to the fishing bait business in the US in the early part of the 20th century whose rise was a function of a growing urban population. The popularity of fishing as a recreational activity coupled with the paucity of native earthworm populations created a high demand that was capitalized on by Depression-era entrepreneurs. By the late 1940s, worm growers were promoting lumbricids as an effective means for farmers to improve the fertility of their soils, often making claims that lacked any scientific basis. In the 1970s, as environmental concerns moved into the public consciousness, researchers began exploring the earthworm’s potential to mitigate waste disposal and soil reclamation in the US, Britain, France, and Japan. Since then researchers have amassed significant data supporting the viability of vermitechnology as a source of fertility (Benitez *et al.*, 1996; Atiyeh *et al.*, 2000a, 2000b; Karmegam *et al.*, 1999; Ozores-Hampton and Vavrina, 2002) and as a means of waste management (Eastman *et al.*, 2001; Edwards, 1998; Ndegwa and Thompson 2001; Wong and Griffiths, 1991), disease suppression (Szczech *et al.*, 1993)**,** and bio-remediation (Ma *et* al., 2002).

While home-scale vermicomposting has rapidly increased in popularity in the industrialized world since the early 1980s, there has been only meager proliferation of municipal- or agricultural-scale vermicomposting facilities. This is due to economic constraints, and resistance to adapting a new technology. There are exceptions, however, whose success might serve to herald a movement of industrial-scale alternative waste disposal. A facility in Tasmania processes 50.5 m^3 $week^{-1}$ of green mulch and MSW (Appelhof *et al.*, 1996). The largest vermicomposting facility in the US processes 68 Gg $year^{-1}$ of cardboard, manure, green waste, and tomato (*Lycopersicon esculentum*) residuals (Sherman-Huntoon, 2000). Edwards (1998) discusses a French system that can convert up to

27% of the total urban waste stream into vermicompost. Nevertheless, extensive large-scale experimentation is necessary to help determine the vermicomposting's potential as a high-volume waste management technology.

The waste disposal situation in less industrialized countries, while similar, is even more threatening due to lack of waste management infrastructure. Economic and environmental instability has led many rural dwellers to large cities in the last few decades. The resulting rapid urbanization has seen a significant rise in waste production. In India, with populations concentrating in urban centers, the organic matter that comprises 70 to 80% of urban solid waste ends up in landfills (Kale, 1998). Two hundred million Gg of solid and liquid human and animal excreta are produced annually in India (Jairajpuri, 1993), which, in addition to the 100 million Gg of agricultural and other organic wastes, has the potential to produce 400,000 Gg of plant nutrients in addition to biogas and ethanol (Senapati, 1993b). Rising fertilizer prices and disillusionment with diminished soil fertility over the years since the adoption of "Green Revolution" chemical-inputs of the 1970s have driven farmers to seek alternative forms of fertility (Kale, 1998). These factors—a large labor force, a high percentage of degradable, organic waste, and limited capital to invest in high-tech waste disposal systems and fertilizers—have made vermicomposting a viable and appropriate waste management technology in India. Several research institutions, non-governmental organizations, commercial enterprises, and farmers have contributed through research, promotion, and training to the widespread adoption of vermicomposting (Ashok Kumar, 1994). The Bhawalkar Earthworm Research Institute has been experimenting since 1981 with vermitechnology, established six large-scale projects in India, and trained over 5,000 farmers in sixteen states (White, 1996). Several agro-industrial facilities rely on vermicomposting to manage waste products such as sugarcane (*Saccharum* spp.) pressmud, distillery sludge, and flower and plant waste from aromatic oil extraction.

Since 1989, Cuba has relied heavily on vermicomposting as a means of disposal of agricultural and municipal waste and as a primary source of soil fertility. With the fall of the Soviet Union, Cuba lost its primary supplier of cheap fertilizers, pesticides, farm equipment, and fuel, as well as its primary agricultural trading partner (Perfecto, 1994; Werner and Cuevas, 1996; Oppenheim, 2001; Funes, 2002; Nova, 2002). Fertilizer imports dropped 77% from 1,300 Gg in 1989 to 300 Gg in 1992 (Werner and Cuevas, 1996). These events and a reduction of Soviet food imports by 50% (Oppenheim, 2001), coupled with a tightened US embargo, brought Cubans precariously close to starvation. A “Special Period” followed where immediate need and a philosophy of low-input sustainability were the foundation for agricultural policy, transforming Cuban agriculture on a national scale. Production was localized into rural community-run cooperatives or urban community gardens, and biological fertility and pest management systems were promoted. In 1994, over 170 vermicomposting facilities producing 700 Gg of worm castings for use as fertilizer (Treto *et al*., 2002). Production over the following four years averaged 600 Gg vermicompost year^{-1}.

2.4.2. Species selection and temperature

While the use of *Eisenia fetida* seems ubiquitous in the literature, there is indeed a wide range of species proving effective as composters. The range of species actually studied, however, is limited. Edwards *et al.* (1984) evaluated the suitability of six different species for decomposing agricultural waste and sludge: *E. fetida*, *Dendrobaena veneta*, *D. subrubicunda*, *Lumbricus rubellus*, *Eudrilus eugeniae*, and *Perionyx excavatus*. They found that while *D. veneta* showed rapid growth and attained a greater weight at maturity than *E. fetida*, its cocoons produced fewer hatchlings.

The choice of species for use in vermicomposting largely depends on temperature. In tropical regions, *E. eugeniae*, the African night crawler, is commonplace as a composting worm and as a source of protein meal (Ashok Kumar, 1994; Kale, 1998). Along with *E. fetida* and *E. eugeniae*, *P. excavatus* and *P. sansibaricus* are well suited to southern regions of India where summer temperatures are lower than in the north (Ashok Kumar, 1994). Gajalakshmi *et al.* (2000a) reported that *Lampito mauritii* and *E. eugeniae* produced more castings per unit volume from a cow (*Bos taurus*) manure and paper waste feedstock than *P. excavatus*. Neuhauser *et al.* (1988) measured growth and reproduction of five species (*D. veneta*, *E. fetida*, *E. eugeniae*, *P. escavatus*, and *Pheretima hawayana*) in aerobically digested sewage sludge. They observed little variation in growth between 15 and 25°C, whereas 30°C was associated with reduced growth rates, and 35°C with mortality. Similarly, Aston (1988) noted lethal temperatures from 25 to 33°C for earthworms common to temperate regions and 34 to 38°C for tropical and sub-tropical species, yet this range is higher than those reported by Edwards (1988): 30°C for *P. excavatus* and *E. eugeniae*.

Neuhauser *et al.* (1988) also found optimum temperature for the growth of *E. eugeniae* was between 20 and 25°C, and 25°C for *P. hawayana*. All five species exhibited optimal cocoon production at 25°C. *E. fetida* was the only species capable of producing cocoons at 15°C, and only *P. excavatus* at 30°C. While *P. excavatus* produced more cocoons over the 20-day reproductive cycle, hatching rates were low. *E. fetida* produced the highest rate of live worms. Edwards (1988) reported tolerance of *E. fetida* to temperatures ranging from 0 to 35°C. Optimal temperatures for cocoon production are often lower than temperatures for rapid growth, likely a response to greater evaporative loss at higher temperatures (Aston, 1988).

2.4.3. Moisture content

Much of the literature states that optimal moisture content (MC) in vermicomposting lies between 80 and 90% (Neuhauser *et al.*, 1988; Beetz, 1998; Edwards, 1998), yet physical and chemical differences in feedstocks may cause slight variations. Kaplan *et al.* (1980) reported maximum weight gain of *E. fetida* in sludge at 75 to 80% MC. Loehr *et al.* (1985) observed increased worm biomass in sewage sludge at a high MC of 85 to 90%. Reinecke and Venter (1985) noted that a 5% difference in moisture content significantly affected clitellum (sexual organ) development in *E. fetida*. In another study, the same authors reported differences in moisture preferences amongst juvenile and clitellated worms and cocoon deposition Reinecke and Venter (1987). Along a moisture gradient, 80% of juvenile worms remained between MC levels of 65 and 70%, whereas clitellated worms were more evenly distributed over MC levels of 60 to 75%. Eighty percent of all cocoons were deposited between 60 and 70% MC. Dominguez and Edwards (1997) examined growth of *E. andrei* in a mixture of pig manure and maple leaves at MC of 65, 70, 76, 80, 85, and 90%. Results indicated a direct relationship between moisture content and growth rate, with maximum growth occurring at 85%. Under different moisture treatments, worms of the same age developed clitella at different ages.

2.4.4. Worm stocking density

There is a considerable range in worm stocking density in the literature. Ndegwa *et al.* (2000) studied the effects of various stocking rates on the vermicomposting of biosolids. Among four initial stocking densities of *E. fetida* they found a density of 1.60 kg m^{-2} to be optimal for the production of worm biomass. Percent growth of earthworm biomass increased as densities increased, but declined at a density of 2.00 kg m^{-2}. This supported the findings of Dominguez and Edwards (1997) who determined that a stocking density of eight earthworms (*E. andrei* oligochaeta) per 43.61 g dry matter (DM) of pig manure to be optimal for sexual development. Frederickson *et al.* (1997) also reported a significant reduction in growth and reproduction of *E. andrei* as stocking densities increased. At lower stocking densities, sexual maturity may be delayed (Dominguez and Edwards, 1997). During the vermicomposting of cow manure and paper waste with *Eudrilus eugeniae*, Gajalakshmi *et al.* (2001a) found that a high stocking and feed rate of 950 g feed for 250 worms per 3 L container produced 6.5 times more castings per unit reactor volume as compared to 75 g feed for 20 worms per 4 L. Most extension literature recommends a stocking density of 5 kg m^{-2} (Sherman-Huntoon, 2000; Slocum, 2002), a much higher density than that found in scientific literature, presumably to ensure a more rapid turnover of material.

2.4.5. Feedstocks

Researchers have explored an enormous variety of agricultural and municipal wastes as potential feedstock for vermicomposting. Manure is perhaps the most palatable of feedstocks to composting worms due to its high rate of nitrogen and consequent rapid decomposition by edible microorganisms. Since the early 1980s, the Rothamsted site in Great Britain has advanced understanding of the vermicomposting potential of various manures—cow and pigs solids and slurries, horse (*Equus caballus*) manure, various poultry litters—as agricultural soil amendments and horticultural growth media (Edwards, 1988). Each type of manure has its benefits and limitations.

Pig manure has the highest nutrient levels of any feedstock, but solids must be separated from the liquid fraction before vermicomposting to lower moisture content to acceptable levels (Edwards, *et al.*, 1984; Phillips, 1988; Edwards, 1998). Wong and Griffiths (1991) compared wastes derived from three pig farming systems: fresh waste collected directly from pens, effluent flushed from pens, and *in situ* composted litter (sawdust and manure). Solids had to be stabilized to prevent overheating prior to vermicomposting. The worms digested the screened solids more efficiently, requiring only 3 g screened solids g worm biomass^{-1} accumulated over a five week period, likely due to a dilution of salt and ammonia levels by hydraulic flushing of pens in the screened. Almost 3 times as much fresh manure directly from the pens was required an equivalent rate of growth, Organic carbon was highest in the screened solids (55% of fresh weight), and moisture was approximately 80%, the optimal level for vermicomposting.

Cow manure is acceptable to *E. fetida* within a few days after separation from a slurry form and is considered the “easiest” waste for vermicomposting (Edwards *et al.*, 1984; Edwards 1998). Hand *et al.* (1988) studied cow slurry as a potential feedstock when mixed with paper waste or peat at 2:1 and 1:1 ratios. Worm growth was 10- to 60-fold higher than controls of peat and paper waste, and the 1:1 ratio was generally associated with increases in worm and cocoon biomass. When comparing freshly separated cow slurry solids to anerobically digested solids, Frederickson and Knight (1988) noted slightly higher nitrogen levels in digested solids, but few overall differences in physical or chemical characteristics of the two finished vermicomposts. Gratelly *et al.* (1996) examined the stabilization of dairy sludge mixed with different bulking agents and found that growth and reproduction of worms was higher than in a control treatment of sheep (*Ovis aries*) manure. They reported increases in nutrient and humic acid concentrations, as well as a 39% reduction in total organic carbon in the dairy waste. Gajalakshmi *et al.* (2001a), testing cow manure + paper waste mixes of 4:1, 5:1, and 6:1, concluded that while a higher proportion of manure increased production of worm castings; the difference was too small to economically justify a higer rate of manure. Mitchell (1997) reported that worms were unable to survive in cow manure with pH of 9.5 or electrical conductivity levels of 5.0 dS m^{-1}.

Poultry litter is a problematic feedstock for vermicomposting due to its high rates of ammonia and soluble salts (Edwards, 1998; Slocum, 2002). Nitrate content greater than 1 g kg^{-1} can result in rapid increases in mortality, with 100% morality occurring between 3 and 4 g kg^{-1}. Soluble salt levels above 5 g kg^{-1} can also be toxic (Edwards, 1988). Léon *et al.* (1992) reported 100% mortality when using chicken (*Gallus domesticus*) manure, but 84 to 100% survival with other undiluted manure substrates. Toxic concentrations of salt and NH_3 in fresh manure may be reduced by pre-composting or stockpiling. Edwards *et al.* (1984) claimed that leaching or composting was necessary for periods of up to three months before ammonia levels were low enough for the addition of worms. Phillips (1988) also recommended stacking litter with high ammonia content outdoors until levels reach 0.5% of initial fresh weight.

Haimi and Huhta (1986) claim, however, that "vermistabilization as a secondary treatment after the thermophilic phase of conventional composting is probably out of the question, because the nutritional value for worms will drop rapidly." While nutrition may not be optimal, the literature is dominated by research using pre-composted material as feedstock. In addition, most commercial vermicomposters use pre-composted material as a feedstock to guarantee a weed-free product, as well as to adhere to federal PFRP requirements. Graziano and Casalicchio (1987) recommended the integration of thermophilic composting and mesophilic vermicomposting as a means of sludge processing, using the coarser compost for "less specialized" crops and the finer, concentrated vermicompost for specialty horticulture. Frederickson *et al.* (1997) measured the reduction of volatile solids (VS) in thermophilic compost and vermicompost of fresh green waste after eight weeks in order to determine organic matter stabilization. They found that vermicomposting reduced VS up to 12% more than composting alone. Two weeks pre-composting followed by six weeks of vermicomposting resulted in a similar reduction. Ndegwa and Thompson (2001) also observed a 45% reduction of total solids (TS) and 13% reduction of VS compared to vermicomposting reductions of 36% for TS and 10% for VS. Other agricultural waste residuals used in vermicompost include potato (*Solanum tuberosum*) waste, brewery waste, crop residues, and spent mushroom (Basidiomycota) waste (Edwards, 1988). Gajalakshmi *et al.* (2001b) studied combinations of the aquatic weed water hyacinth (*Eichhornia crassipes*) and cow manure, and found that vermicompost production was equal when water hyacinth was added to cow manure at rates of 6:1 and 4:1. Grappelli *et al.* (1987) found that a mixture of 300 L of olive oil wastewater per cubic meter of organic municipal solid waste (MSW) was an effective feedstock in a municipal vermicomposting pilot facility.

Many researchers have studied the use of earthworms to digest sewage sludge. Stabilization of sludge can occur three times faster when stocked with worms due to increases in microbial decomposition (Edwards, 1988). Neuhauser *et al.* (1988) reported a reduction of volatile solids in aerobic sludge stocked with *E. fetida*, thus reducing the probability of anaerobic putrefaction of the material. As fresh weight percentage of total solids increased above 16%, however, worm biomass decreased due to stress associated with low moisture. Kaplan *et al.* (1980) evaluated activated sludge and found that worm growth was higher when soil was incorporated with the sludge or placed on top. Mortality of worms occurred at pH levels less than 5 and greater than 9, the range supported by most of the literature, and at salt concentrations greater than 0.5%.

The implications for vermitechnology use in wastewater treatment facilities are considerable and merit continued research. In Florida, the City of Ocoee wastewater treatment facility successfully used vermicomposting to reduce human pathogens (fecal coliforms, enteric viruses, helminth ova [*Ascaris spp*.], and *Salmonella spp.*) to well below EPA accepted levels in domestic wastewater residuals (Eastman *et al.*, 2001). In addition to the potential for pathogen reduction, Kale (1993) posits that the concentration of heavy metals and toxic organic compounds in the worm can remove those materials from the sludge, thereby minimizing quantities entering the environment. In contrast, Ma *et al*. (2002) reported increased availability of lead (Pb) by 48%, and zinc (Zn) by 25% following inoculation of mixtures of mine tailings + soil with *Pheretima* spp. They attributed these increases to the presence of dead or decaying earthworms in the treatments. Nevertheless, the authors suggested that while increased availability may increase leaching potential, it also allows for uptake by phytoremediating plant species.

2.5. Vermicomposting systems

Unlike thermophilic composting, which depends on the rising temperature of the organic mass, vermicomposting can be successfully managed on large or small scales, and is perhaps most widely practiced in kitchens in homemade bins or crates on a small scale. On an industrial or commercial level, however, there are generally three main vermicomposting systems: windrows, single-batch reactors, and continuous flow systems (Edwards, 1998; Beetz, 1999; Sherman-Huntoon, 2000). Perhaps the greatest challenge to vermicomposting is to assure that the feedstocks do not attain a temperature high enough to begin the thermophilic process of decomposition, as this would kill the worms (Subler, 2002). The necessity for proper aeration also limits the total depth of applied material to 0.5 to 1.0 m (Phillips, 1988). Production is greatest when temperature, moisture, and aeration are adequate, and feedstock is within acceptable chemical parameters (Edwards, 1998).

2.5.1. Windrows

Windrows range from 1 to 2.5 m wide and can be as long as 0.5 km. They require a well-drained soil as a base, or a sloped concrete pad to prevent accumulation of water and anaerobic decomposition from occurring at the bottom of the windrow (Edwards, 1998). Feedstock is repeatedly placed on top of the windrow at a thickness of 3 to 10 cm. Haimi and Huhta (1986) claim that worms can work a maximum thickness of 5 cm of sewage sludge. Additional feedstock is layered as it is converted to castings and can be harvested before the windrow reaches a height of 0.5 m to prevent thermophilic temperatures that can be fatal to worms (Haimi and Huhta, 1986). Mitchell (1996) reported two-fold greater reductions of organic matter in windrows 20 cm deep than in windrows 30 cm deep. In Cuba windrows are often formed with a manure spreader that has been modified so that feedstock is spread no wider than the wheelbase of the implement. After 10 to 12 days, signs of surface feeding are visible and an additional layer of 7 to 10 cm is added. When the windrow reaches 65 cm—the height of the tractor axle—worms are harvested by adding a fresh layer of feedstock, irrigating the windrow, and scraping off the top layer with a front-end loader (Werner and Cuevas, 1996). The wedge system is a modified version of the windrow method in which new feedstock is added at a 45-degree angle against one face of the mature windrow (Sherman-Huntoon, 2000). Heavy applications of feedstock can result in overheating and worm mortality, or increase the time required for uniform digestion of the feedstock. While the windrow system is the simplest, leaching losses of nutrients are greatest under intensive irrigation (Graziano and Casalicchio, 1987b; Edwards, 1998).

2.5.2. Single-batch reactors

Batch reactors range in size from small boxes or bins to large, walled beds, or troughs. Giraddi (2000) compared a pit system, a “heap” windrow system, and a “brick column” batch reactor system during the rainy, winter, and summer seasons in India. He found that pits and brick column reactors fostered the greatest worm reproduction and biomass, resulting in a higher conversion of waste into vermicompost. He concluded that the ability of the two systems to maintain moisture led to increases in biomass. While the most feasible for experimentation and home-scale vermicomposting, Edwards (1998) claimed batch systems were too labor-intensive for effective production since vermicompost must be removed before new waste can be added. However, the total removal of material following composting allows for cleaning and is a means of avoiding mite infestation (Beetz, 1999). Without labor constraints, this method has proven effective in Cuba, where large concrete feeding troughs serve as batch reactors (Werner and Cuevas, 1996). Some of the more successful operations in the US also use the bed system and rely on family or migrant labor to harvest mature vermicompost (Sherman-Huntoon, 2000). Worm beds at an eastern North Carolina hog farm are stocked with separated solids using a manure spreader and cooled with spray nozzles mounted on a hose running the length of each bed. Castings are harvested with shovels and screened to separate worms.

2.5.3. Continuous flow systems

The continuous flow system was described as a raised-bed system that allows air flow and harvesting through a mesh grate below, with feedstock evenly distributed along the top via a mechanical tracked gantry (Edwards, 1998; Beetz, 1999; Sherman-Huntoon, 2000). While these continuous flow reactors have the highest initial capital investment of all vermicomposting systems, they have the greatest potential for processing substantial quantities of organic waste. One 36.5 × 2.4 m bed made of dairy industry machinery in Washington is capable of processing 2.7 Mg of waste daily (Sherman-Huntoon, 2002). A California farmer who produced high-quality vermicompost in eight to twelve months in a windrow system was able to produce the same quantity in 40 to 60 days after he switched over to a continuous flow reactor (Chambers, 2002). Using or modifying readily available agricultural equipment for construction greatly reduces initial cost and facilitates maintenance (Subler, 2002).

2.6. Physical and chemical characteristics of vermicompost

In vermicomposting, the relatively quick fragmentation of particulate matter is achieved by the grinding muscular gizzard of the worm with the help of enzymatic secretions such as amylase, cellulase, protease, lipase, chitinase, and lichenase. Also, the presence of certain actinomycetes aids the formation of clay-humic complexes and other cementing agents (Senapati, 1993a). The result is a loosely aggregated, granular material whose stability depends on organic matter and moisture concentrations and bacterial and fungal polysaccharides structure (Kale, 1993; Subler, 2002). The final percentage of particles less than 5 mm in size is greatly increased by the vermicomposting process (Elvira *et al*., 1987).

While nutrient content in a finished vermicompost certainly varies according to the initial feedstock, the nutrient content of the digested waste is often lower than that of the raw material. Some nitrogen loss is balanced by a reduction in volume, but the overall N content of a vermicomposted waste may be lower than the feedstock due to volatilization, leaching, or denitrification (Buchanan *et al*., 1988). Nevertheless, the vermicomposting process generally transforms nutrients into a plant available form (Edwards, 1998), but mineralization may be affected by organic carbon present in the substrate; phosphorus (P), molybdenum (Mo), iron (Fe), and Zn content may also be indirectly related to mineralization by their effect on soil microbial activity (Buchanan *et al*., 1988). Soluble salts and electrical conductivity (EC) generally increase over the course of the vermicomposting (Kale, 1998; Masciandaro *et al*., 1997), but Warman and AngLopez (2002) reported an eventual decrease in electrical conductivity, supporting the earlier findings of Elvira *et al.* (1998).

2.6.1. Nitrogen

Casalicchio and Graziano (1987a) examined the chemical properties of composted and vermicomposted sewage sludge, MSW, and a mixture of the two. They concluded that soluble N in the MSW was transformed into an insoluble compound, while total N decreased in sludge during the experiment. In addition, at the beginning of the experiment NH_4^+ and NO_3^- made up less than 50% of soluble N, but accounted for almost 100% by the end.

Buchanan *et al*. (1988) studied the mineralization rates of a soil amended with five different vermicomposts. In all treatments, a priming effect occurred: higher quantities of N mineralized in the first week than in subsequent weeks. The authors attributed this increase to labile portions of dried microbial biomass and residual soil enzymes present in the soil. Mineralization of the amended soils paralleled that of the control, but was significantly highest in the two sludge-based treatments. Ammonium content of horse manure and household waste vermicomposts were not significantly greater than the control until week 5. The researchers also attempted to assess common parameters of vermicompost quality: C:N ratio and mineralization. They reported highly correlated total N and inorganic N (r=.98), but no significant correlation was observed between C:N ratio and inorganic N.

Mitchell (1997) reported a 17% increase in N concentration in cow manure vermicomposted in a 1.5 m × 1.5 m × 0.2 m bed (0.225 m^3 manure), but a 13% decrease in a 1.5 m × 1.5 m × 0.3 m bed (0.09 m^3 manure) and a 3% decrease in a 3.5 m × 1.5 m × 0.25 m bed (0.19 m^3 manure). Decreased N concentrations were associated with high levels of unconverted material. Additionally, the author concluded that nutrient concentrations were reduced following vermicomposting due to assimilation into worm biomass. Similarly, Ndegwa *et al.* (2000) reported that while N concentration did not change during vermicomposting, total N reductions paralleled decreases in total solids, and they concluded that N was either volatilized or taken up in the worms' tissue. Elvira *et al.* (1998), reported 55 to 100% increases in total Kjeldahl N (TKN) concentrations due to mineralization of organic matter. Similarly, Warman and AngLopez (2002) observed 42 to 85% increases in total N in three vermicomposted wastes after 45 and 68 days. After 90 days, however, total N concentration had returned to levels only slightly above initial concentrations of 13, 24, and 20 g kg^{-1}.

2.6.2. Phosphorus

Most literature indicates increased P concentration during vermicomposting due to loss of DM (Elvira *et al.*, 1998; Ghosh, et al, 1998; Chowdappa *et al.*, 1999). Ndegwa *et al.* (2000) observed increases between 14 and 39%. Ghosh *et al.* (1998) also reported rapid mineralization of P in worm treatments of five organic wastes. Total mineral P increased, as well as the amount of unavailable P bound to aluminaum (Al), Fe, and calcium (Ca). Most P was fixed as aluminum phosphate following its release from the organic to inorganic form. They attributed lower rates of ferric P fixation to low oxygen; in addition, the iron was present mostly in the Fe^{+2} form, restricting P fixation as ferric phosphate. Kumar and Singh (2001) actually inoculated millet (*Pennisetum glaucum*) and cow manure vermicompost with several strains of nitrogen-fixing and phosphate-solubilizing bacteria. All treatments showed increases of available P and N.

2.6.3. Potassium and micro-nutrients

Increases and decreases of K and micro-nutrients during vermicomposting have been reported in the literature. Elvira *et al.* (1998) reported significant reductions of total K by the end of the vermicomposting process which they attributed to its high water solubility and leaching of the windrows. Casalicchio and Graziano (1987a) reported highly variable decreases in P, K, Ca, and Mg, but no statistically significant relationships. Similarly, Bansal and Kapoor (2000) observed N increases in vermicomposted crop residue and cow manure, but no difference in P, K, or copper (Cu). Gratelly *et al.* (1996) reported a decrease in total Cu concentration, but increases in total K, Ca, Mg, Fe, Mn, and Zn concentrations during the vermicomposting of dairy sludge. Albanell *et al.* (1988) also reported increases in P, Na, and K that they attributed to accelerated mineralization of organic matter. Wong and Griffiths (1991) warned of the potential accumulation of toxins in the worm gut and reported Zn levels in vermicompost five times greater than those in the original pig manure feedstock. Edwards (1998) noted that low levels of Mg in the final product is common due to low Mg levels in many manures.

2.6.4. Carbon, humification, and pH

Vermicomposting leads to a breakdown of carbon and a reduction of volatile solids, resulting in the stability of the finished product. Vincelas-Akpa and Loquet (1997) analyzed OM transformations in composted and vermicomposted maple leaf yard waste, and found a decrease in the C:N ratio from 62 to 27 over 9 months in the vermicompost compared to a drop from 62 to 30 in the compost waste. While vermicompost and compost treatments both showed losses of organic matter until the seventh month, the initial decrease was greater in vermicompost. In addition, percentage of C actually increased in vermicompost after month 7, whereas it stabilized in the compost. Chowdappa *et al*. (1999) also reported a decrease of 62 to 24 in C:N ratio during vermicomposting of areca (*Areca catechu*) leaves compared to 62 to 33 for a thermophilic composting process. Casalicchio and Graziano (1987) reported no differences in total organic C between compost and vermicompost treatments of sewage sludge, a MSW, and MSW + sludge. After 90 days of vermicomposting the MSW, the ratio of humic to fulvic acids was 18% greater than in compost. The ratio of humic acid to organic C (humification) was 42% greater in vermicomposted MSW than composted MSW, and 30% greater in the vermicomposted MSW + sludge compared to composting. High humic fractions can result in increased CEC in waste processed with worms. Albanell *et al.* (1988) reported a greater CEC (17%) in vermicomposted sheep manure + cotton waste compared to composted feedstock after 12 weeks. Similarly, humic acid concentration was 31% greater in vermicompost than in compost. Warman and AngLopez (2002) also reported increases in CEC from 45 to 80 cmol kg^{-1} after 90 days of vermicomposting kitchen + yard waste.

The vermicomposting process generally neutralizes the pH of the substrate. This may be attributed to $CaCO_3$ secretions in the worm gut that have an alkalizing effect on the feedstock (Buchanan *et al.*, 1988; Senapati, 1993a). Most of the literature attributed this neutralization to humification of the substrate. Alter and Mitchell (1992) associated pH increases in a 1:5 soil solution amended with vermicompost extract (200g vermicompost 500 ml H_2O^{-1}) to high proportions of humic substances that formed chelates with aluminum ions. They reported 98% reduction in Al in solutions with pH greater than 6 and 90% reduction in solutions with a pH of 4. These observations support the conclusions of Albanell *et al.* (1988), who observed pH decreases from 9.1 to 7.2 and increases in CEC from 35.5 to 79.6 cmol kg^{-1} during vermicomposting of sheep manure + industrial cotton wastes. The authors attributed the rise in CEC to increases in humic acids and production of CO_2 by microbial populations during vermicomposting. Haimi and Huhta (1986) and Elvira *et al.* (1998) came to the same conclusion. Elvira and colleagues concluded that 20 to 43% of total organic carbon was lost to CO_2 production and extractable carbon increased, as did the humic fraction. The resulting lower C:N ratio, low water soluble C, and high degree of humification indicated a rapid stabilization of the initial substrate.

2.6.5. Microbial characteristics

Due to the mesophilic transformation of organic matter, vermicompost contains greater microbial populations than thermophilic compost, leading to greater potential for odor reduction and nutrient mineralization (Kale, 1993). Edwards *et al.* (1984) identified large populations of Gram-negative Enterobacteriaceae in vermicompost feedstock. Additionally, a large proportion of the microbial population was composed of protozoa and fungi. The authors suggested that as the worm feeds on organic matter, it digests some of the microbial constituents, and ultimately increases the surface area of the remaining material passing through its gut. This can increase the potential for microbial colonization and subsequent decomposition of the waste material. There are microbial populations—fungi, protozoa, and bacterium—inside the worm gut itself (mostly in the foregut) that are encouraged by an internal pH between 6.3 and 7.3 (Senapati, 1993a). Albanell *et al.* (1988), however, noticed a marked decline in microbial colony forming units (CFUs) after six weeks of vermicomposting sheep manure and cotton waste. Similarly, Hand *et al.* (1988) reported no significant difference in bacterial or fungal populations in cow slurry treated with and without worms. After six weeks, populations decreased more rapidly in vermicompost treatments than in controls. This may have been due to the fact that the control remained in a mesophilic state, rather than achieving a thermophilic state of composting that would have considerably reduced microbial populations.

2.7. Agricultural applications of compost and vermicompost

2.7.1. Effects on soil physical characteristics

The use of compost and vermicompost as soil amendments can have many positive effects on soil physical characteristics following high rates of application. High levels of organic humic matter soil amendment in the form of compost improve soil structure by increasing porosity and reducing the bulk density of an amended soil. Polysaccharides and other polymeric substances present in OM act as aggregating compounds (Masciandaro *et* al., 2000) and increase micropores in the soil. Since a composted MSW may contain more than 50% OM, sufficient application can positively impact soil organic matter. An application of 34 Mg ha^{-1} (~ 1 cm-thick layer) is necessary to noticeably raise soil OM. The resulting increase in humic aggregates can increase the water-holding capacity of a mineral soil by 5 to 10% by increasing the number of small pores (McConnell *et al*., 1994).

Many field studies have demonstrated decreases in soil bulk density and increases in porosity resulting from compost application. Evanylo and Sherony (2002) reported decreases in bulk density after two annual applications of the full rate for field production (55 Mg DM ha^{-1}) and 20% of the full field rate (11 Mg DM ha^{-1}). Bulluck *et al*. (2002) noted an increase in OM and decrease bulk density in soils amended with “alternative” amendments, such as cotton gin trash, hay manure compost, or yard waste, compared to those using commercial synthetic fertilizers. Bulk density in soils treated with non-synthetic amendments was 1.01 g cm^{-3} versus 1.17 g cm^{-3} in synthetically fertilized soils, and OM was 2.83 versus 2.00 g kg^{-1}. Aggelides and Londra (2000) amended a clay soil (Humic Fluvaquent) and a loamy soil (typic Xerochrept) in Greece with 0, 75, 150, and 300 m^{3} ha^{-1} of a MSW, sludge, or sawdust compost. Compost application reduced bulk density of the loamy soil by up to 20% in the 300 m^3 ha^{-1} treatment. Total porosity was improved up to 33% compared to no compost application. Increased rates of compost application resulted in increased hydraulic conductivity: 33 to 95% in the loamy soil, 55 to 168% in the clay soil. Increases in water retention capacity and aggregate stability followed a similar pattern. Debosz *et al*. (2002) also reported an 88% increase in aggregate stability after 11 months in a sandy loam amended with household waste compost (DM) at 17 Mg ha^{-1}. In another experiment, the aggregate stability of a semiarid beidellitic clay soil increased 13 % over a two-year period with an annual application of 30 g MSW compost kg $soil^{-1}$ (Caravaca *et al*., 2001). Aggregate stability was significantly correlated with organic C and humic matter in the fine silt fraction of the soil.

Since C is rapidly mineralized then leached or lost as CO_2 following microbial respiration, improvements to soil structure are often only detectable after several years of compost application. Gonzales and Cooperband (2002) observed no significant decreases in bulk density in a fine, silty, mixed, mesic Typic Argiudoll amended with three types of compost after one year. However, after two and three years, soil bulk density was lower in plots planted with spirea (*Spirea japonicum*) and barberry (*Berberis thunbergia*) shrubs than in plots planted with juniper (*Juniper chinensis*). The authors suggested that the greater root biomass of the two species may have displaced soil with a higher density or that increased root exudation may have increase soil aggregation. Plots receiving incorporated compost followed by a surface application resulted in 56% soil porosity, while porosity was 53% in treatments where compost was incorporated only. Compost application led to a two- to seven-fold increase in saturated hydraulic conductivity compared to unamended plots (2.89×10^{-3} cm sec^{-1}). Additionally, volumetric soil moisture content in surface-applied treatments (0.264 m^3 m^{-3}) was greater than in incorporate-only (0.235 m^3 m^{-3}) and control (0.242 m^3 m^{-3}) treatments. Field water holding capacity (WHC), however, was greater in incorporated treatments than in surface-applied or control plots. Humpert (2000) reported compost applications of 4.5 Mg ha^{-1} on every vine row of a California vineyard to reduce erosion, increase water holding capacity, and augment microbial populations.

Vermicompost with a high concentration of small aggregates may actually increase the bulk density of an amended potting substrate. Atiyeh *et al*. (2001) found that due to smaller particle size the bulk density of pig manure vermicompost was 2.25 times greater than Metro-Mix 360. When vermicompost was added to Metro Mix (MM) at concentrations of 5, 10, 25, 50, and 100% by volume, bulk densities of the potting medium increased proportionally. Total porosity of the 5 to 50% mixtures was reduced 1 to 6%, and percent air space 33 to 53%. The authors concluded that in 5, 10, and 25% MM mixes, vermicompost improved the water holding capacity of the Metro Mix while the Metro Mix improved the percent porosity and airspace of the vermicompost. Masciandaro *et al*. (2000) noted an increase in total surface shrinkage in vermicomposted aerobic and anaerobic municipal sludge. They associated the formation of small cracks (< 500 µm) in the substrate with an increase in small aggregates, which serve as an index of improved soil structure.

2.7.2. Cation exchange capacity, pH, and carbon

Application of compost can also result in agronomic benefits in the soil chemical characteristics. An increase in total C in the form of OM leads to an increase in CEC, thereby increasing the number of exchange sites for mineral nutrients available for plant uptake. A compost application of 34 to 67 Mg ha^{-1} can increase CEC in most mineral soils by 10%, thereby reducing leaching of fertilizer nutrients (McConnell *et al*., 1994). Generally, increases in total C or SOM occur either after the first year or following successive applications, as C from an initial application may be cycled too quickly to be observed in the first year. In one study, soil total C in the first year was not affected by a single application of 22 Mg ha^{-1}, but in the second year was 28% greater than the no compost control (Grandy *et al*., 2002). In another treatment, plots were left unamended following 4 or 5 years of annual compost applications. In the first unamended year, plots contained 28 g kg^{-1} more C than unamended controls, and in the second year, 46 g kg^{-1} more than controls. In contrast, Tester (1990) observed a 24% loss of C at 13 cm in the first year following application of 134 Mg sludge compost ha^{-1} to a mesic, coated Typic Quartzipsamment. The author attributed this loss to leaching or decomposition. Some researchers have posited that compost application acts as a priming agent for SOM mineralization. Sikora and Yakovchenko (1996), however, did not observe any stimulation of SOM in a fine-loamy, siliceous, mesic Typic Hapludult amended with MSW or sludge composts.

Compost OM can act as a liming agent in agricultural soils. Neutral to slightly alkaline composts can increase the pH in most acid soils, reducing the potential for Al and Mn toxicity (McConnell *et al*., 1994). Increases in pH are directly proportional to the proton and Al consumption capacity of the OM, specifically of humic and fulvic substances containing high carboxyl, phenolic, and enolic functional groups. As organic anions are adsorbed, a corresponding release of hydroxyls raises the pH of the soil (Wong *et al*., 1998). Some humic substances and organic acids (*e.g.*, citric, oxalic, succinic, and tartaric) can complex with Al, thereby lowering the Al toxicity potential. While complexes with acids can be easily broken due to microbial activity, humic complexes are more recalcitrant (Mokolobate and Haynes, 2002). Mokolobate and Haynes (2002) reported a reduction in solution Al from 41% to less than 20% in an acid soil amended with four different organic residues. The residues increased CEC and soluble C content, as well as available P and exchangeable Mg and Ca. Wong *et al*. (1998) reported a linear relation between proton consumption capacity and total base cations in a tropical acid soil amended with plant residue compost, urban waste compost, farmyard manure, or peat. Eghball (1999) applied P- and N-based rates of beef feedlot manure compost to a corn crop. P-based applications were supplemented with N fertilizer up to a net 151 kg N ha^{-1}. Because manure contained 9 g $CaCO_3$ kg^{-1}, four years of application resulted in $CaCO_3$ rates of 1730 kg ha^{-1}. Soil pH increased significantly In N-based treatments compared to P-based applications. Similarly, Bulluck *et al*. (2002) noted a two-fold increase in soil Ca concentration over 2 years following compost applications of 9 and 20 Mg ha^{-1} to two Typic Hapludult loams.

2.7.3. Effects of compost and vermicompost on soil fertility and plant growth

The improvements to soil physical structure, soil fertility, and soil microbiological properties associated with compost application all promote plant growth, as a growth medium for transplants and a soil amendment for field crops. Several studies have evaluated the effect of vermicompost-amended potting media on plant growth greenhouse production. Generally, potting medium with 10 to 20% vermicompost by volume provides adequate fertilization for transplant growth (Subler *et al*., 1998; Atiyeh *et* al., 2000a; Ozores-Hampton and Vavrina, 2002).

In one study, germination rates of greenhouse tomatoes increased up to 15% when vermicomposted pig manure was mixed with potting medium at 20, 30, and 40% by volume. The highest marketable yield of fruit was reported in the 20% mixture. Treatments consisting of 100% vermicompost led to smaller growth and fewer leaves than other treatments, due to high-moisture and possible phytotoxicity (Atiyeh *et al*., 2000a). Benitez *et al*. (1996) used leachate from a sheep manure vermicompost (100% and dilutions of 10 and 30%) in a germination bioassay with cress (*Lepidium sativum*) seeds. The pure leachate reduced germination due to its high salt content and associated electrical conductivity, while the 30% dilution led to germination indexes greater than 60%. In plant tissue analyses, however, only 38% of manure-N was recovered in spinach (*Spinacia oleracea*) plants, compared to 68% uptake of fertilizer-N. Karmegam *et al*. (1999) evaluated germination efficiency, shoot length, roots length, nodulation, weight, and yield of green gram (*Phaseolus aureus*) grown in a 3:1 mixture of potting soil and vermicomposted cow manure. Germination in vermicompost was 93% versus 84% germination in a control (3:1 mix of potting soil and bio-digested manure slurry). Additionally, green gram biomass increased 46%, and shoot height by 28%. Seed pod numbers increased by 35%, pod length increased by 13%, seeds per pod by 20%, and seed yield per plant by 52%. Root nodulation in vermicomposted treatments increased 78% above controls, suggesting increased microbial activity in the rhizosphere. Sagar *et al*. (2002) compared growth of *Ocimum sanctum*, a crop used for essential oil, in vermicomposted cow manure, farmyard manure, urea, and a control growth medium. While oil yield was 15 g kg^{-1} in all treatments, leaf weight was 25% higher in vermicompost treatments than control and plant weight 52% higher. Ozores-Hampton and Vavrina (2002) grew organic tomato transplants in Florida using five different mixtures of worm castings, peat, and vermiculite (0:70:30, 18:52:30, 35:35:30, 52:18:30, and 70:0:30). Nitrogen concentrations of the worm castings were 26 g kg^{-1}. The control was fertilized with 200 mg 20-4.4-8.3 L^{-1}. During summer and fall, tomato growth increased linearly with vermicompost content, from 0.08 to 0.22 g DM plant^{-1} whereas shoot biomass of fertilized controls was 0.11 g DM plant^{-1}. Since worm casting C:N was low (16.5), organic N was likely mineralized rapidly during the warmer growing seasons.

Due to more labor-intensive production, vermicompost use is most prevalent in high-end home gardening or organic transplant markets. Nevertheless, in less industrialized countries it is often applied on a field scale. In Cuba, for example, vermicompost was applied on fields at a rate of 4 Mg ha^{-1}, much less than the 45 Mg ha^{-1} of cow manure previously applied. Vermicompost applications resulted in a 31% increase in production and reduction in leaf chlorine content from 10 to 4 mg g^{-1} (Werner and Cuevas, 1996).

Low nutrient concentrations in compost may limit its use in transplant production. Klock-Moore (2001) used a yard waste + biosolids compost as an amendment to potting medium. While CEC and nutrients were greater in substrates amended with 30, 60, and 100% compost, the low fertilizer rates (6, 12, 24 or 48 kg 13N-5.7P-10.8K 100 m^{-2}) did not supply sufficient nutrients for growth of *Impatiens* spp. and *Salvia* spp. flowers. In a field situation, compost has proven successful as a fertility source when applied at heavy rates to crops, depending on the rate of organic N mineralization.

Due to low concentrations of nutrients, compost benefits agricultural production more as a soil amendment than as a fertilizer. Organic farmers who rely solely on compost as a fertility source may need to apply compost at rates >10 Mg ha^{-1}. At these high rates, compost may no longer be an economical means of crop fertilization. Additionally, high agronomic rates may result in phytotoxicity if soluble salts are too high (Madejon *et al*., 2001). A compost feedstock largely determines its value as a fertilizer. Most manure and vegetative-based composts are high in P, but low in K. Long-term use can therefore result in overapplication of P and K deficiency (Eghball and Power, 1999b; McConnell *et al*., 1994). Additionally, N availability can be limited if compost C:N is too high. If the C:N ratio is greater than 30, soil N is usually initially immobilized and not available for plant uptake (Eriksen et al., 1999; Mamo et al, 1998).

Total compost N generally ranges from 5 to 20 g kg^{-1}, the majority of which is in the unavailable organic form. While many farmers and state extension services assume that 40 to 50 % of this N will become available (NCDA & CS, personal communication), others have determined lower rates of mineralization. Eghball (2000) observed 11% mineralization of organic N from a beef cattle feedlot manure compost applied to a corn field the previous autumn. Mineralization was similar in conventional and no-till systems. In a similar experiment, beef feedlot compost N availability was 20% (Eghball and Power, 1999a). The same authors reported that compost applications based on P requirements for a corn crop supplemented with fertilizer N resulted in similar yields to an N-based application (7.5 versus

7.2 Mg ha^{-1}), but after four years, soil available P was two-fold lower following P-based applications (75 versus 150 g P kg^{-1}) (Eghball and Power, 1999b). Mamo *et al*. (1998) applied 0, 45, 90, and 180 Mg MSW compost (DM) ha^{-1} to two different Mollisols (a sandy mixed, Udothentic Haplaboroll and a coarse-loamy mixed Udic Argiboroll). Two other MSW composts were applied at 90 Mg ha^{-1}. In the composts with low carbon to nitrogen (C:N) ratios, approximately 8% of compost N was available in the first year, whereas the compost with the high C:N actually immobilized soil N and reduced corn stands. After three years, N availability of initial MSW compost ranged from 3 to 10%. In a study using 226 kg composted ^{15}N-labeled wheat straw + manure ha^{-1}, approximately 65 % of compost N was assimilated by a wheat (*Triticum aestivum*) crop. Only 2.6% was utilized by a subsequent barley (*Hordeum vulgare*) crop (Thomsen, 2001). Iglesis-Jiménez (2001) reported 50 % availability of MSW compost N in the first two months following an application of 60 Mg ha^{-1} to a ^{15}N-labelled Eutric Cambisol. Clearly, N availability is highly variable and largely dependent on the compost feedstock and maturity, soil chemical characteristics, and environmental changes in moisture and temperature, posing challenges to nutrient management in systems that utilize compost.

Many experimental rates, however, are far higher than a grower would ever apply due to budget constraints. While compost is relatively inexpensive, its transport is costly. Low rates of application may not provide sufficient N for optimum crop growth. Farmers wishing to transition from conventional to organic systems often express concerns about reductions in yields when relying on compost as a fertility source. Nevertheless, some researchers have observed yield increases when using compost in conjunction with standard or reduced rates of fertilizer. Maynard (2002a) applied 112 Mg leaf compost ha^{-1} on a dry weight basis for three years to sweet corn plots previously cropped hairy vetch, and noted that yields in plots receiving compost + full fertilizer rates (591 kg 10-10-10 ha^{-1}) were 56% greater than fertilizer control treatments without compost. Compost applied to a half-rate of fertilizer (295 kg 10-10-10 ha^{-1}) resulted in 42% greater yield than no-compost half-rate controls. In a study comparing controlled microbial composted dairy manure and hay to a conventional methyl bromide (MB)-based strawberry (*Fragraria* spp.) production system, Grabowski (2001) found no significant difference in yields between compost and MB treatments over three years. On the other hand, yields in non-fumigated control plots were on ~66% of those harvested in MB plots in years two and three. Sullivan *et al*. (2002) applied two composts (food waste + yard trimmings + paper and food waste + wood waste + sawdust) at 78 Mg ha^{-1} containing 870 to 1000 kg total N ha^{-1} to plots before seeding with tall fescue (*Festuca arundinacea*). Plots were fertilized with ammonium nitrate at five rates (0, 17, 34, 50, and 67 kg N ha^{-1}). While compost did not significantly affect grass yield or N uptake in first year, yield increased 3% each in the second and third years. Nitrogen use efficiency, however, did not improve. They concluded that compost N availability was limited by decomposition of compost OM in the soil and noted that a C:N ratio greater than 15 may have led to temporary net immobilization.

The high agronomic rates of compost required for fertility in organic production have raised concerns of heavy metal and P accumulation from manure-based composts. One 6-year study of a clay-loam calcareous soil (Fluventic Xerochrept) amended with MSW compost over six years revealed significant increases in Cu, Zn, and Pb, as well as in Cr in the last two years. Corn uptake of Pb was three times greater in amended soils than in an unamended control. Uptake of other metals was twice as great as in the control (Gigliotti, *et al*., 1996). Zinc and copper are present in many poultry feeds, serving as an antibiotic/preservative. As a result, repeated annual application of poultry litter and other animal wastes can lead to increased metal concentrations in soil (Kpomblekou *et al*., 2002; Sims and Wolf, 1994; King *et al*., 1990), leading to concern among some North Carolina organic farmers (Mikkelsen, 2000). Researchers have found that applications of poultry litter can also increase cadmium (Cd) and Pb concentrations in the soil (Shuman, 1998).

Nevertheless, the presence of compost OM can help to mitigate mobility of certain metals in the soil solution, due to increased surface area and concomitant increase in adsorption sites. Zhou and Wong (2001) examined the effects of dissolved OM from sludge compost on Cu sorption on two soils, an acidic sandy loam and a calcareous clay loam. An increase in OM in both soils significantly reduced Cu sorption by both soils. While sorption increased with increasing pH in unamended soils, the researchers observed a reduction in sorption at pH > 6.8 in compost-amended soils. They attributed this decrease to leaching losses associated with soluble OM and Cu complexes. Another experiment studied the effect of 0, 100, and 300 Mg sludge compost ha^{-1} on Cd uptake by corn plants grown on a Southeastern Piedmont soil amended with Cd salt at 0, 5, 10, 20, and 50 mg Cd kg soil^{-1}

(Shuman *et al*., 2002). The compost applications resulted in greater CEC and OM content in the soil, and reduced phytotoxicity due to immobilization of soluble Cd by OM. At the 10 mg Cd kg soil^{-1} rate, Cd concentrations in compost-amended soils were 30 mg kg^{-1}, whereas concentrations in namended soils were 105 mg kg^{-1}. In a related study, Shuman (1998) found that spent mushroom compost lowered Cd in the exchangeable and OM fractions of both a coarse-textured and a fine-textured soil. The compost also lowered Pb in the OM and exchangeable fractions of the soils.

The sorption capacity of compost OM can also have a deleterious effect on boron (B) uptake by plants. At high rates of B application (1 mmol kg^{-1}), Yermiyahu *et al*. (2001) observed reductions of B uptake by pepper (*Capsicum frutescens*) as rates of cow manure and straw compost increased from 30 to 100 g compost kg soil^{-1}. Bittenbender *et al*. (1998) also noted reductions in leaf nitrate and B concentrations in *Macadamia* spp. trees following a modest application of 10 Mg compost ha^{-1}.

In sandy, marginal soils in less-industrialized nations, P-deficiency is frequently cited as the reason for low yields. Phosphorus is often bound by Al or Ca and consequently unavailable for plant uptake. Field applications of compost or manure rarely provide sufficient P, as available P is quickly immobilized by other elements in the soil. In countries where P fertilizer-use is restricted by high costs, many researchers and extension workers have proposed incorporating natural rock phosphate (RP) into compost piles. Compost OM and P-solubilizing bacteria present in the compost microbial biomass help to mineralize P for plant uptake. Singh and Amberger (1995) applied wheat straw composted with Mussoorie and Hyper rock phosphates to ryegrass. A significant amount of insoluble P in both RPs became available during composting. Yields of ryegrass fertilized with single superphosphate were not significantly different than ryegrass grown in RP-amended compost. In another study, on a P-deficient semiarid Vertisol in India, Manna *et al.* (2001) found that a single 10 Mg ha^{-1} application of four different composts enriched with RP and inoculated with P-solubilizing bacteria (*Bacillus polymyxa* and *Pseudomonas striata*) resulted in soybean yields, P uptake, and biomass DM equal to treatments fertilized with 26.2 kg single superphosphate ha^{-1}. In Senegal, millet and sorghum grown on soil amended with 2 Mg compost ha^{-1} amended with 30 kg P_2O_5 ha^{-1} yielded 38 to 42 % more than treatments of 2 Mg unamended compost ha^{-1} (Sène and Guéye, 1998).

2.7.4. Soil microbial populations and plant pathogen suppression

In conventional agriculture, incidence of pests and plant disease is generally curtailed through the use of pesticides and fungicides. While these synthetic inputs are generally effective, pathogens may gain resistance after repeated applications, thus jeopardizing future production and forcing farmers to depend on increasingly intensive control programs or seek alternative forms of bio-control (Locke *et al*., 2001; Damicone, 1996). Organic certification standards prohibit the use of such fungicides, leading growers to seek alternate forms of disease control. Similarly in less industrialized countries, where chemical inputs are often not used due to high cost and limited availability, pathogens must be managed by natural techniques or amendments.

The application of mature compost colonized by mesophilic bacteria and fungi can result in increased biotic diversity in the soil. Microbial biodiversity can improve the resilience and stability of an agroecosystem by mitigating over-colonization by pathogenic populations (Bamforth, 1999; Altieri, 1995). In an experiment comparing different concentrations of pig manure vermicompost in a potting medium, Atiyeh *et al.* (2001) found that dehydrogenase enzymatic activity (DHA, a common indicator of microbial respiration DHA) in 100% vermicompost was almost a hundred-fold greater than in Metro-Mix. DHA activity in the potting media was 32 times greater with incorporation of 50%. Masciandaro *et al.* (2000) reported decreasing DHA in worm-degraded aerobic and anaerobic sludge-amended soils. Madejon *et al*. (2001) reported an increase in soil enzyme activity (DHA, beta-glucocosidase, and urease) during an incubation of soil amended with 50 Mg ha^{-1} of MSW, paper sludge, and tree waste composts. Pascual *et al*. (1997) noted similar increases in biomass C and basal respiration in an arid soil amended with MSW and sewage sludge composts. Tarkalson *et al*. (1998) observed significant increases of mycorrhizal population of bean (*Phaseolus vulgaris*) roots in coarse-silty, mixed, mesic Durixerollic Calciorthid topsoil and subsoil amended with manure and composted manure. At 21 days after planting, less than 5% colonization had occurred in compost and manure treatments, but increased to 58% at 66 days.

High populations of beneficial microbes in compost and vermicompost allows for biological control of pathogenic fungi. Bio-control, or "general suppression," is carried out by the activities and interactions of soil microorganisms that compete with pathogens for resources or produce antibiotic chemicals (Baker, 1968). Generally, pathogen spores in compost-amended soils are more densely covered with beneficial fungal and bacterial propagules, thereby limiting their infectivity. These beneficial populations often parasitize the hyphae of pathogenic fung. Additionally, by consuming the amino acids, carbohydrates, and volatile ethanols and aldehydes exuded from root and seed tissue and decomposing plant residue, beneficial microbes may reduce resources required by pathogenic fungal spores for germination (Stone, 2002). While antibiosis and resource competition by beneficial microbial populations may lead to decreases in pathogenic fungi, increased numbers of plant growth-promoting rhizobacteria (PGPR) may also lead to increased induced systemic resistance (ISR) in the plant. ISR is a means of disease suppression is based on strengthening physiological defenses against pathogenic fungi, bacteria, and viruses. PGPR (mostly *Bacillus* spp. and *Pseudomonas* spp.) presence leads to increases in chitinases, beta-1 and 3-glucanases, peroxidases, and other pathogenesis-related proteins, as well as the accumulation of anti-microbial low-molecular weight substances, and the formation of protective biopolymers (lignin, callose, glycoproteins) (Liu *et al*., 1995; Wei *et al*., 1996; Chen *et al*., 2000).

Several greenhouse studies have demonstrated the efficacy of compost and vermicompost in suppressing plant disease. Tuitert *et al.* (1998) observed suppression of *Rhizoctonia solani* in cucumbers (*Cucumis sativus*) planted in a potting mixture containing 20% mature household waste compost. However, in mixtures containing 1 month-old immature compost, pathogen growth was stimulated. The authors concluded that suppression was associated with high densities of cellulolytic and oligotrophic actinomycetes present in mature compost at a density 200-fold higher than in immature compost. In a split-root experiment, Lievens *et al.* (2001) reported up to four-fold reductions of root-rot (*Pythium ultimum*) incidence in cucumber roots growing in household waste and yard trimming compost. Additionally, less root rot in plants germinated in compost mix was noted compared to in straight potting medium. Szchech *et al*. (1993) inoculated treatments of pure peat, pure cow manure vermicompost, and mixtures of peat with 10% and 20% vermicompost with *Phytopthora nicotianae*, *Fuasarium oxysporum*, and *Plasmodiophora brassicae*. Infection of tomato seedlings by *Phytopthora* was 75 to 300% less in vermicompost treatments than in the peat-only control. The vermicompost treatments also reduced and prevented clubroot disease (*Plasmodiophora*) development in cabbage (*Brassica oleracea capitata*) plants.

In a field experiment, Bulluck and Ristaino (2002) reported that southern blight (*Sclerotium rolfsii*) incidence was only 3% in field tomatoes amended with composted cotton gin trash while incidence was 67% in plots amended with synthetic fertilizers. Propagule densities of beneficial *Trichoderma* spp. fungi and fluorescent *Pseudomonas* spp. bacteria were more than two-fold greater in plots amended with compost or swine manure than in fields amended with inorganic fertilizer sources. Consequently, *Fusarium* spp. populations were significantly lower in compost-amended plots. Grabowski (2001) used a controlled-microbial-compost (30% dairy manure, 30% waste hay, 30% waste silage, 5 % finished compost, 5% clay soil) as an alternative to the conventional fumigant methyl bromide in North Carolina strawberry production. Methyl bromide treatments exhibited 100% root colonization by *Rhizoctonia fragariae* in Year 2 whereas compost treatments experiences only 20% colonization.

2.8. Economic considerations

A criticism of organic agriculture by offered by conventional agriculture pundits is that organic producers rely heavily on compost and other costly inputs. Several economic analyses of compost production and use in the industrialized and developing world have been conducted, revealing the potential benefits of composting as resource-efficient, environmentally beneficial waste management technology and soil amendment. A Michigan State University study compared costs of composting manure from a 120-cow dairy farm to costs of daily haul and long-term liquid manure pit storage (MSU, 2003). Annual net cost of composting ranged from $7,600 to $13,700 while annual cost of daily-haul averaged $7,900 and long-term storage $14,300.

Initial investment on equipment and labor vary considerably depending on the composting system and will ultimately affect the profitability of the operation. An analysis of production costs by the British Columbia Ministry of Agriculture, Food and Fisheries (1996) compared passive and turned windrow systems to aerated static pile composting. Assuming annual inputs of 2,000 Mg manure with 20 % DM and 1,400 Mg sawdust bulking agent, and total compost production of 1,800 Mg, a passive windrow system requiring a total investment of \$50,000 Canadian and 271 hours year^{-1} labor would incur annual operating expenses of \$45,000, averaging \$25 Mg^{-1}. A turned windrow system consisting of a tractor, turner, hard composting pad, and buildings for curing, and storage, processing the same volume would require 745 hours year^{-1} labor and a total investment of \$190,000. Annual operating expenses would come to \$68,000, averaging \$21 Mg^{-1}. An aerated static pile would require an initial investment of \$171,000 for an aeration system and buildings for composting, curing, and storage. With an annual labor requirement of 596 hours, operating costs would run \$80,000, or an average \$44 Mg^{-1}. Relative to other waste management technologies, costs are modest.

Other economic analyses have focused on the profitability of compost use. A study conducted by the Rodale Institute for the Pennsylvania Energy Office compared two rates of compost application to broiler litter, conventional chemical fertilizer, compost + fertilizer, and a legume cover crop (Reider *et al.*, 1991). Due to the high costs of material and spreading the compost, compost treatments initially resulted in net incomes that were lower than other treatments, at \$337 to \$436 ha^{-1}. Conventional fertilizer treatments were most profitable at \$618 ha^{-1}, followed by legume (\$510 ha^{-1}) and broiler litter (\$506 ha^{-1}). However, an analysis of per hectare Liters of Diesel Fuel Equivalents (LDFE), which includes the fuel required for fertilizer production, revealed that no significant difference between high compost rate (847 LDFE ha^{-1}) and conventional fertilizer application (958 LDFE ha^{-1}). Other amendments were much more efficient than conventional fertilization and high rate of compost application: low rate of compost application (660 LDFE ha^{-1}), broiler litter (401 LDFE ha^{-1}), and legume (477 LDFE ha^{-1}). The report recommends that future policy factor the long-term consequences of fuel use in fertilizer production and encourage compost use by offsetting production costs with a tipping fee of \$2.50 to \$3 m^{-3} paid to farmers. A certified organic premium for production could also increase the profitability of compost use over conventional fertilization. DeLuca and DeLuca (1997) also factored in the cost of petroleum in fertilizer when estimating the potential savings of using composted manure from confined animal feedlot operations (CAFOs). They hypothesized that compost applications to irrigated corn could save 8.6×10^{9} joules ha^{-1} or the equivalent of 181 L diesel fuel ha^{-1}.

Since vermicomposting generally requires more labor than thermophilic composting, economic constraints affecting vermicomposting in industrial nations vary considerably from those in the less-industrialized world where the movement towards sustainable agriculture arises out of immediate necessity. The high cost of labor requires mechanization of mid- to large-scale facilities in industrialized nations, while in the rest of the world, a large pool of unskilled labor allows large-scale vermicomposting to be managed without machinery. In Cuba, the success of the sustainable agricultural revolution relies heavily on volunteer labor based on incentive plans or substitution for military service (Perfecto, 1996; Oppenheim, 2001).

Chowdappa *et al.* (1999) calculated that vermicomposting of leaf waste from one hectare of an arecanut plantation in India could net a profit of 11,114 rupees (~\$246[1]) and provide 50% of N, 33% P, and 26% K needed for arecanut production. Ashok Kumar (1994) reported a similar analysis, yet the viability of both analyses relies on very low labor expenditures. Fieldson (1984), on the other hand, evaluated the economic viability of hog waste vermicomposting in Britain and concluded that a vermicomposting system would be profitable enough to hire one additional full-time employee on a 5,000 head or larger farm. He hypothesized that a centralized system of pig solids separation and worm harvesting would be profitable in areas with high densities of livestock farms and where transport costs could be minimized. The advent of new continuous flow reactors greatly reduces the labor demands of vermicomposting, but requires large initial capital. A 907 Mg year^{-1} facility would cost \$100,000, comparable to a thermophilic facility processing the same amount of material (Sherman-Huntoon, 2000). On a small scale, however, it requires little initial investment and minimal labor (Beetz, 1998).

Vermicompost largely remains a high-priced, niche market commodity in the industrialized world. Its profitability depends on supply and demand dynamics (Fieldson, 1984), as well as a stable economy and disposable incomes. It is critical that we further explore and place value on the potential of vermicompost's potential as an agricultural amendment if we are to promote it is a low-tech waste disposal system.

2.9. Conclusion

The growing volume of research conducted on compost production and utilization in recent years serves as an indicator of increasing interest in compost's potential inclusion as a soil

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[1] Based on the exchange rate in March, 2004.

amendment and as waste management option for agricultural systems. The many studies discussed in this review attest to the multiple benefits associated with compost application to agricultural soils, including improved porosity, water-holding capacity, CEC, nutrient levels, reduced bulk density, and liming effect. Nevertheless, it would be imprudent to consider compost as a panacea organic amendment, or “short-cut” to sustainability. Indeed, much of the research reviewed also demonstrate the risks of compost application such as phosphorus and heavy metal loading, and economic analyses have revealed some of the high costs associated with compost application to fields. Further research is needed to more fully elucidate some of these constraints to indicate situations when compost production and use might be economically viable. Indeed, closer scrutiny of compost’s integral role—as a waste management technology and as a soil amendment—in sustainable and transitioning farming systems is advisable prior to its widespread promotion and adoption.

Chapter 3: Carbon and nitrogen dynamics in composted and vermicomposted mixtures of swine manure and wheat straw

3.1. Introduction

Livestock and poultry production are the mainstay of North Carolina's agricultural economy and the livelihood of many farmers in the state. In 2000, 3,600 hog producers raised 9.3 million head, valued at $1.6 billion. Livestock production ranks first in cash receipts at 17.4% of NC's total agricultural earnings (NCDA & CS, 2002). With each hog producing 2.7 to 4.3 kg of waste per day (Hamilton, *et al.*, no date), waste management is clearly a pressing environmental concern. The lagoon system of collecting and storing liquid waste, while simple and cost-effective, is environmentally precarious in a region averaging 1200 to 1300 mm annual precipitation (and high risk for hurricanes and flooding). Separated solids are commonly spread on fields adjacent to production areas and the effluent pumped and sprayed on pasture or row crops. Nevertheless, the application of manure to fields has been shown to lead to high nitrate (NO_3^-) and salt levels in the soil (Tillman and Surapaneni, 2002) and high nitrate and phosphate (PO_4^-) concentrations in runoff (McLeod and Hegg, 1984). The abundance of low-quality baled forage harvested from effluent-irrigated fields poses an additional management concern, as the hay can contain excessively high nitrate concentrations for livestock consumption and often considered to be waste product (Poore, *et al.*, 2000). It is therefore imperative to seek cost-effective alternatives methods of managing hog waste.

Composting is an effective means of managing agricultural waste products and recycling nutrients within farming systems. Amending soils with compost increases soil organic matter content, cation exchange capacity (CEC), and total nutrient levels, while lowering soil bulk density, improving infiltration, and reducing surface runoff (Bulluck *et al.*, 2002; Gonzalez and Cooperband, 2002). The immobilization of excess nitrate and phosphate in compost also helps prevent nutrient export in runoff. Research has demonstrated that nitrate leaching to groundwater can be reduced when soil is amended with compost compared to inorganic fertilizers (Maynard, 1993) or to semi-composted farmyard waste compared to pig manure slurry (Beckwith *et al.*, 1998). While the slow mineralization of nutrients in most mature compost limits its use as a primary source of fertility during the initial cropping season, yield increases have been reported up to two and three years after compost application (Evanylo and Sherony, 2002; Maynard, 2002; Sullivan *et al.*, 2002). Additionally, high populations of beneficial microbes in compost can effectively control plant pathogens such as *Rhizoctonia solani*, *Phytopthora nicotianae*, *Fusarium oxysporum*, and *Pythium ultimum* (Tuitert *et al.*, 1998; Lievens *et al.*, 2001; Grabowski, 2001).

During aerobic composting, mesophilic microorganisms consume oxygen and carbohydrates solubilized during bacterially mediated enzymatic hydrolysis of hemicellulose and cellulose in organic wastes. The microbial metabolism heats the substrate, resulting in an increase in the thermophilic microbial population and the release of carbon dioxide (CO_2) (Epstein, 1997; Eiland *et al.*, 2001; Druilhe *et al.*, 2002). While the majority of soluble carbon (C) is lost as CO_2, some water-soluble carbon may be lost as leachate under excessively moist conditions. Similarly, excess moisture can also lead to leaching of nitrogen (N). If the carbon to nitrogen (C:N) ratio is less than 25, microorganisms mineralize organic N (de Bertoldi *et al.*, 1984), leading to an increase in ammonium (NH_4^+) and a decrease in organic N. If aeration is inadequate or pH is less than 8, ammonium may be volatilized and lost as ammonia (NH_3^+). As compost stabilizes, the NH_4^+ fraction nitrifies to NO_3^- and becomes available for plant uptake. If NH_4^+ levels are high, however, the compost is considered unstable (Bernal *et al.*, 1998b). Another indicator of compost maturity is the humification (ratio of humic to fulvic acids) of C and a concomitant increase in CEC (Vincelas-Akpa and Loquet, 1997; Bernal *et al.*, 1998b; Tomati *et al.*, 2000). The C:N ratio will vary depending on the initial substrate, and should not be used as the sole parameter to identify a mature compost. Nevertheless, a decrease in C:N, indicating a reduction in C mineralization, generally correlates with stability (Bernal *et al.* 1998a; Bernal *et al.* 1998b; Eiland *et al.*, 2001).

Vermicomposting is the use of earthworms to degrade organic waste at ambient temperatures, optimally between 20 and 25ºC (Edwards *et al.*, 1984; Aston, 1988, much lower than those achieved during the thermophilic period of composting. It is a widely used low-input, unmechanized means of utilizing both agricultural and municipal wastes in less industrialized countries such as India and Cuba (Ashok Kumar, 1994; Werner and Cuevas, 1996). Research has shown that high nutrient concentrations, high CEC, and fine granular physical properties of vermicompost are excellent characteristics for transplant production (Subler *et al.*, 1998; Atiyeh *et al.*, 2000b; Ozores-Hampton and Vavrina, 2002). Its resulting popularity in horticultural and organic vegetable production has created a niche market for vermicompost producers. As with compost, vermicompost can contain high microbial populations shown to suppress disease in seedlings (Szczech *et al.*, 1993).

Many studies have attempted to characterize the physical and chemical characteristics of various vermicomposted substrates. The degradation of waste particulate matter is due to physical grinding by the gizzard muscle in the gut of the worm and aided by secretions of enzymes. The worm casting, or vermicompost, contains a higher percentage of well-aggregated particles less than 5 mm than the original feedstock substrate (Senapati, 1993a; Elvira *et al*., 1998). Soluble salts and electrical conductivity initially increase during the vermicomposting process (Masciandaro *et al*., 1997; Kale, 1998), but then decrease over time as the waste stabilizes (Elvira *et al.*, 1998; Warman and AngLopez, 2002).

The trend towards an increase in nutrient concentration in vermicompost is well documented in the literature and is generally attributed to rapid mineralization of the organic form of the nutrient (Albanell *et al.*, 1988; Gratelly, *et al,* 1996, Elvira, *et al*., 1998; Chowdappa *et al.*, 1999; Bansal and Kapoor, 2000). Nevertheless, Ghosh *et al.* (1998), noted that mineralized P was quickly fixed to aluminum, iron, or calcium ions. Mitchell (1997) reported an increase in the ratio of NO_3^- to NH_4^+ over thirteen weeks in a cow manure vermicompost. Casalicchio and Graziano (1987) found that in a municipal solid waste (MSW) vermicompost, NH_4^+ and NO_3^- comprised only 50% of soluble N at the beginning of the experiment but nearly 100% after three months. Researchers have attributed losses of total N mostly to leaching and volatilization and to a lesser extent incorporation in worm tissue (Buchanan *et al*., 1988; Elvira *et al*., 1998; Ndegwa *et al.*, 2000). Some research has reported greater decreases in C:N ratios (Vincelas-Akpa and Loquet, 1997; Chowdappa *et al.*, 1999) and greater humification (Casalicchio and Graziano, 1987) in vermicompost than in compost. Greater proportions of humic fractions lead to elevated CEC (Albanell *et al.*, 1988; Warman and AngLopez, 2002), lower pH, and a more rapid stabilization of waste in vermicomposted substrates (Haimi and Huhta, 1986; Masciandaro *et al.*, 1997).

Our objective was to compare the carbon and nitrogen dynamics of thermophilically composted pig manure and straw to that of vermicomposted substrate. Additionally, we were interested in how these dynamics differed depending on when the substrate was introduced to the worms. Some researchers have recommended pre-composting feedstock in order to reduce pathogens (Graziano and Casalicchio, 1987; Frederickson *et al.*, 1997) and weed seed viability (Eghball and Lesoing, 2000), while others have maintained that fresh manure or mixed substrate is optimal (Edwards, 1998). Another observation of interest was how straw content and particle-size reduction of the straw affected these dynamics. The addition of bulking agents with high concentrations of slowly degrading forms of C can help to reduce volatilization of N as NH_3^+ (Paredes *et al.*, 2000; Barrington *et al.*, 2002). We hypothesized that nutrient concentrations would be greater and that decreases in C:N ratios would be greater and occur more rapidly in vermicomposted substrate than in compost piles. We also expected steep declines in C:N ratios in treatments using chopped straw, and a slow decrease in carbon over time at higher levels of straw in the substrate mixture.

3.2. Materials and Methods

A composting and vermicomposting substrate mix study was conducted at the Center for Environmental Farming Systems (CEFS) in Goldsboro, NC, in a sheltered facility from late-June to early-September 2002. Average daily air temperature during the experiment ranged from 19.9 to 31.5ºC. A 2500 sow farrow-to-wean operation in Greene County, NC, provided pig manure solids separated with a Hoffland solids separator (Hoffland Environmental, Inc., Conroe, TX[1]). Composite samples of both pig manure solids and wheat were analyzed for nutrient and dry matter content at the beginning of the experiment [Table 3.1]. Because C concentration of wheat straw was not provided in the analysis, we assumed a C content of 40% (Hadas, *et al.*, 1998) to determine initial pile mixtures [Table 3.2]. All samples were analyzed at the North Carolina Division of Agriculture and Consumer Services (NCDA & CS) Agronomic Division lab, Raleigh, NC.

Table 3.1: Initial chemical characteristics of manure and straw used in the experiment

	pH	**DM**	**C**	**N**	**P**	**K**	**Ca**	**Zn**	**Cu**
Material		%	----------	----------	g kg^{-1}	----------	----------	------ mg	kg^{-1} -----
Manure	6.3	33.1	229	10.56	9.72	3.10	28.36	240	116
Straw	--	91.6	400†	7.20	0.70	12.10	1.10	12	2

† *estimated*

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[1] The mention of a registered trademark does not indicate endorsement by North Carolina State University.

Table 3.2: Carbon and nitrogen concentrations and C:N ratio of initial mixtures (Week 0)

Straw	C concentration*	N concentration	C:N
%	-------------------------g kg^{-1}---------------------		
0	229.3	10.6	21.7
7	242.6	10.3	23.5
16	259.8	10.1	25.8
25	277.0	9.7	28.5
36	297.9	9.4	31.9

** 7, 16, 25, and 36% straw mixtures assume straw C concentrations of 400 g C* kg^{-1}

3.2.1. Compost piles

Based on dry matter weight (DM) calculations, manure was weighed in 190 L plastic garbage cans on a strain gauge load cell scale and wheat straw (*Triticum aestivum*) was mixed in with a pitchfork at rates of 7, 16, 25, and 36% DM. One treatment level consisted of unchopped straw and the other treatment was straw chopped with a Goossen 5400 bale chopper (Harper Industries, Harper, KS). A control pile (0%) contained no straw. Pile mixtures were assigned randomly. A windrow thermometer (Reotemp Instrument Corp., San Diego, CA) was used to take daily temperature readings from top center, bottom center, north and south sides of each pile and a mean temperature was calculated. Piles were manually turned and aerated with pitchforks at least twice weekly. To maintain moisture in the piles at approximately 50 to 60%, piles were watered with a hose during aeration, and a "squeeze test" was used to determine moisture content (NCAER, 1999). Eight composite samples were taken from each pile at Week 3, 6, 10, and 13 for analysis.

3.2.2. Vermicomposting treatments

Treatments of raw material vermicomposting feedstock were started the same day as compost piles were prepared. Using the same dry weight proportions calculated for the piles, 11.3 L plastic bins were filled with mixtures of 7, 16, 25, and 36 % straw and manure at two levels of straw length (chopped and unchopped), with three replications. Water was added gravimetrically to each bin to bring all treatments to 2.5 kg (80% moisture), and then stocked with 100 g of earthworms (*Eisenia fetida*, Kazarie Worm Farm, Trenton, FL). Storage locations for the bins were randomly assigned. After three days, bins were checked for worm mortality, and bins with 100 % mortality were removed from the experiment. Bins with evidence of partial mortality were restocked with additional worms, again bringing bin content weights up to 2.6 kg (2.5 kg of feedstock + 100 g worms). Four repeated measurements were taken from an arbitrary sample of eight bins to determine mean treatment temperature. At weeks 3 and 6, all bins were sampled for C:N and nutrient analysis.

The second treatment using pre-composted feedstock began on Week 3. Based on compost dry matter concentration determined by the previous week's analysis, 2.5 kg compost was weighed out for three replicates of each of the nine piles. To prevent mortality, compost was allowed to cool for several days before water was added to bring each bin to an equal weight (2.5 kg). Each bin was stocked with 100 g of worms. Temperature measurements were recorded when each bin was composite-sampled for analysis at 3, 7, and 10 weeks after beginning the treatment (Weeks 6, 10, and 13 of the experiment).

3.2.3. Statistical Analysis

Compost piles were not replicated due to labor constraints, and therefore cannot be statistically compared to vermicomposting treatments or between levels of chop (chopped straw vs. unchopped). All data were analyzed using linear regression (PROC REG, SAS Institute, Cary, NC) and a general linear model procedure (PROC GLM). Means between levels of chop within a given vermicomposting treatment were compared using LSMEANS, while means across both vermicomposting treatments at Week 6 were compared using a protected LSD.

3.3. Results and discussion

3.3.1. Temperature, moisture, and physical characteristics

Temperatures in all compost piles peaked between 48 and 54ºC on either day 3 or 4 of composting [data not shown], but did not achieve sustained temperatures to meet EPA standards of pathogen reduction which require temperatures of 55ºC for three consecutive days during the coolest period of aeration, or 40ºC for five consecutive days and 55ºC for three consecutive days (Ndegwa and Thompson, 2001). Lower than anticipated temperatures may have been due to the small size of piles and insufficient watering. The manure control (0 %), 7%, and 16% chopped piles all gradually decreased in temperature over the three weeks that pile temperatures were recorded, rising slightly on day 14 following a watering event. Generally unchopped piles with high straw content (25 and 36%) remained 10 to 15ºC cooler than treatments with less straw during the first two weeks and began to increase to temperatures above the others after two weeks. Piles with 25% and 36% straw began to reheat following day 14 and attained higher temperatures than lower rates of straw. Temperatures of the 36% unchopped treatment rose more slowly than those of the chopped treatment, attaining 48ºC by day 20. The volume of substrate in all compost piles visibly diminished two-fold over the thirteen weeks of the experiment, as carbon degraded.

Several raw feedstock treatments experienced complete worm mortality during the first couple of days of the experiment due to high substrate temperatures. All 0% controls and 7% chopped treatments experienced high mortality, as well as two 16% chopped, two 25% chopped, and one 7% unchopped treatments. Worm bins across three treatments experienced partial mortality (one 25% chopped, two 7% and two 16% unchopped) and were restocked. An arbitrary sample of eight treatments indicated average temperatures of material in the bins to be 30.5ºC three days after the experiment began. While Edwards (1988) notes that *E. fetida* can tolerate temperatures up to 35º, Aston (1988) reported mortality in temperate species between 25 and 33ºC. Substrate temperatures averaged between 25 and 27ºC at both sampling dates. At the first sampling date, water had accumulated at the bottom of bins with high straw content (36% chopped and unchopped) in more than 50% of the bins, leading to some anaerobic decomposition. Over the six weeks of the treatment, worms did not visibly degrade the straw fraction in any treatment.

In pre-composted feedstock vermicompost, substrate temperatures averaged between 25 and 27ºC on all three sampling dates. Similar to the raw feedstock treatments, water had accumulated at the bottom of bins with high straw content (36% chopped and unchopped) by the first sampling date, leading to some anaerobic decomposition. Due to decreasing moisture content with time, several treatments experienced mortality between the second and third sampling dates (all 7% and 25% chopped, two 36% chopped, and one 16% unchopped), so no observations were recorded for these bins at week 13. Over the nine weeks of vermicomposting, visible degradation of the straw fraction of the substrate was minimal in all bins.

Table 3.3: Mean carbon concentrations in raw feedstock vermicompost and compost piles at Weeks 3, 6, 10, and 13

Treatment	Chop	Straw concentration (%) 0	7	16	25	36
		----	----	$g\ C\ kg^{-1}$	----	----
Week 3						
Raw feedstock	**Chopped**	n.d.	n.d.	119.0	94.7	148.3
	Unchopped		196.7	181.7	209.2	197.8
				NS	†	NS
‡Compost piles	**Chopped**	175.4	166.2	100.3	189.5	173.5
	Unchopped		136.7	80.9	137.9	242.0
Week 6#						
Raw feedstock	**Chopped**	n.d	n.d	89.7c	135.4	128.0b
	Unchopped		144.8	158.9a	182.1	183.7a
				*	NS	**
Pre-composted feedstock	**Chopped**	157.1	135.8	108.9b	171.7	140.0b
	Unchopped		151.1	113.2b	111.1	116.0b
			NS	NS	**	NS
LSD across treatments (p<0.05)			NS	14.3	NS	43.2
‡Compost piles	**Chopped**	134.4	127.0	100.9	145.6	167.9
	Unchopped		173.5	59.5	101.0	132.2
Week 10						
Pre-composted feedstock	**Chopped**	126.5	131.2	131.7	150.3	156.5
	Unchopped		153.3	113.1	98.0	112.8
			NS	NS	**	*
‡Compost piles	**Chopped**	154.3	158.8	117.4	143.1	156.5
	Unchopped		215.1	106.8	114.0	112.8
Week 13						
Pre-composted feedstock	**Chopped**	137.4	n.d.	106.4	n.d.	124.3
	Unchopped		151.1	99.4	102.5	102.5
				NS		NS
‡Compost piles	**Chopped**	123.2	122.8	102.1	107.1	92.2
	Unchopped		153.2	108.1	122.5	67.4

#Week 6 means in the same column followed by different letters are statistically different (p<0.05).
*** indicates significant difference between chopped and unchopped levels of straw at p<0.01, * at p<0.05, † at p<0.10,* NS *not significant (p>0.10).* n.d. *indicates no data.*
‡Piles were not replicated and cannot be statistically compared to vermicompost treatments or between chop levels.

3.3.2. Carbon dynamics

Total C concentration in all compost piles decreased by Week 3, and then decreased more gradually for the duration of the experiment [Table 3.3]. Concentrations rose slightly at 10 weeks, then returned to previous levels at Week 13, possibly due to a watering event and CO_2 losses due to aeration. By Week 13, total C concentrations in chopped straw piles were 49 to

69% lower than in original mixtures. In unchopped piles, C concentrations decreased 37 to 78% over the duration of the experiment. The manure control (0% straw) declined 46% by Week 13.

By Week 6, unchopped raw feedstock C concentrations had decreased 34 to 40%, while chopped treatment C declined 51 to 65%. Chop effect was significant at Week 3 ($p<0.10$) and Week 6 ($p<0.05$), likely due to the rapid decomposition of the chopped straw. Decreasing particle size of a compost bulking agent such as straw can lead to more rapid degradation of C fractions due to increased surface area available for microbial activity (Barrington *et al*., 2002). At Week 6 (3 weeks thermophilic composting + 3 weeks vermicomposting) C concentrations in unchopped pre-composted feedstock treatments were significantly lower ($p<0.05$) than unchopped raw feedstock treatments. This can be attributed to limited degradation of straw by worms in the raw treatment relative to the rapid degradation of straw C during the thermophilic pre-composting period.

Contrary to expected results, C concentrations at Week 10 in unchopped pre-composted feedstock treatments were lower than in chopped treatments ($p<0.05$). This was possibly due to the loss of soluble C during watering events. Since temperatures in unchopped treatments did not attain the same levels as chopped, loss as CO_2 was unlikely. This anomaly may also have been an artifact of sampling; earthworm activity separated straw and manure/castings into distinct layers, requiring manual mixing of the vermicompost at each sampling date. By the end of the experiment, C levels in chopped pre-composted feedstock were 49 to 69% lower than original mixes. In unchopped treatments, C concentrations were 37 to 77% lower than at Week 0. The pre-composted manure (0% straw) control experienced a decrease of 46%.

3.3.3. Nitrogen dynamics

Following 13 weeks of composting, total N concentrations in compost piles were highly variable [Table 3.4]. Chopped treatments ranged from increases of 18 and 51% to decreases of 3 and 4% in chopped treatments. Unchopped treatment N generally decreased from 3 to 34%, likely due to leaching at each watering event as high straw piles absorbed water poorly. Total N concentrations in 7% straw mixtures increased 22 and 52% and manure (0% straw) increased 18%, likely due to a loss of mass during the composting process.

Table 3.4: Mean nitrogen concentrations in raw feedstock vermicompost and compost piles at Weeks 3, 6, 10, and 13

		Straw concentration (%)				
Treatment	**Chop**	**0**	**7**	**16**	**25**	**36**
		g N kg^{-1}				
Week 3						
Raw feedstock	**Chopped**	n.d.	n.d.	8.5	6.6	10.2
	Unchopped		14.5	13.2	15.7	13.7
				NS	*	NS
‡Compost piles	**Chopped**	15.2	14.2	8.1	13.0	12.6
	Unchopped		11.9	6.1	10.6	14.3
Week 6#						
Raw feedstock	**Chopped**	n.d.	n.d.	6.8c	10.0	10.1b
	Unchopped		11.7	12.3a	14.3	14.2a
				*	NS	*
Pre-composted feedstock	**Chopped**	13.0	11.9	8.9b	13.9	12.5ab
	Unchopped		11.5	8.5b	9.4	9.4b
			NS	NS	**	NS
LSD across treatments (p<0.05)			NS	1.4	NS	3.9
‡Compost piles	**Chopped**	12.2	11.0	8.8	12.0	13.7
	Unchopped		16.1	5.1	8.6	10.0
Week 10						
Pre-composted feedstock	**Chopped**	10.1	11.9	11.0	13.2	14.8
	Unchopped		11.6	9.0	8.4	9.9
			NS	NS	**	**
‡Compost piles	**Chopped**	16.6	16.1	11.4	12.9	14.8
	Unchopped		20.8	9.7	10.5	9.9
Week 13						
Pre-composted feedstock	**Chopped**	11.3	n.d.	8.8	n.d.	11.4
	Unchopped		12.0	7.3	8.9	9.4
				NS		NS
‡Compost piles	**Chopped**	12.1	12.6	9.7	14.7	9.0
	Unchopped		15.7	9.8	10.2	6.2

#Week 6 means in the same column followed by different letters are statistically different ($p<0.05$).
*** indicates significant difference between chopped and unchopped levels of straw at $p<0.01$, * at $p<0.05$,* NS *not significant ($p>0.10$).* n.d. *indicates no data.*
‡Piles were not replicated and cannot be statistically compared to vermicompost treatments or between chop levels.

Total N concentration in unchopped raw feedstock treatments generally increased over the first three weeks and declined by Week 6 (9 to 52%), whereas chopped treatments dropped slightly by the first sampling and returned to concentrations only slightly below initial levels. This decrease could have been due to volatilization under anaerobic conditions or incorporation into worm tissue (Buchanan *et al.*, 1988; Elvira *et al.*, 1998; Ndegwa and

Thomspon, 2000). Differences between chopped and unchopped raw feedstock were significant at Weeks 3 and 6 ($p<0.05$) in treatments with high levels of straw (16, 25, and 36%), suggesting N volatilization or incorporation of N into worm biomass.

Additionally, N concentrations in unchopped raw feedstock were 14 to 51% higher ($p<0.05$) than in pre-composted feedstock at Week 6. This can be attributed to leaching or volatilization loss of N during the thermophilic pre-composting stage prior to vermicomposting. Concentrations of N in unchopped pre-composted feedstock were significantly less ($p<0.01$) than in chopped treatments at Weeks 6 and 10, possibly a result of leaching losses of N during the pre-composting stage. Since pile temperatures did not rise above 50°C, it is unlikely that N was lost to volatilization.

3.3.4. C:N ratios

Averaged over time, C:N ratios were generally high in mixtures with straw content of 25% and 36% [Figure 3.1, Table 3.5], likely due to high concentrations of recalcitrant forms of C such as lignin or cellulose (Eiland *et al.*, 2001; Vincelas-Akpa and Loquet, 1997). Overall, raw feedstock vermicompost C:N did not vary between percentages of straw, likely a result of unpalatability to the worms. Low C:N ratios in the compost piles and pre-compost treatment were likely due to the thermophilic phase of composting when soluble carbon is quickly metabolized by microbial populations (Epstein, 1997; Eiland *et al.*, 2001). In the raw feedstock vermicompost treatment, on the other hand, low temperatures may have slowed degradation of carbon.

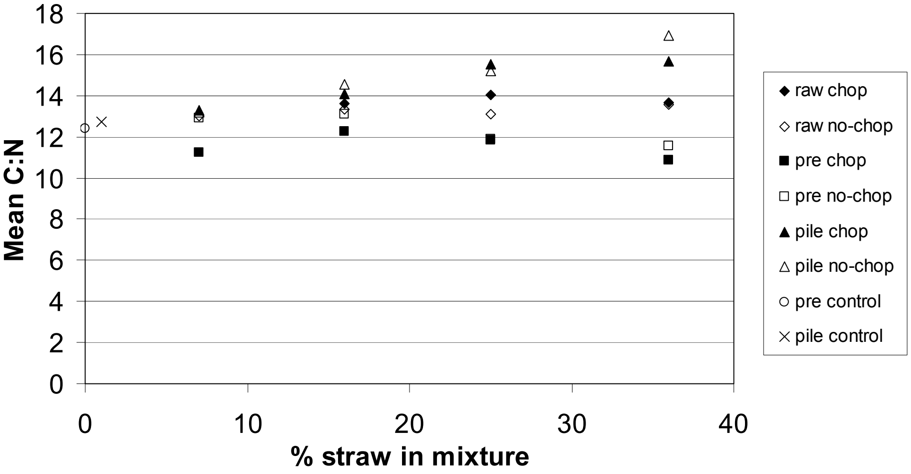

Figure 3.1: Treatment effects on C:N ratio averaged over time versus straw content

Table 3.5: Mean C:N ratios of raw feedstock vermicompost and compost piles at Weeks 3, 6, 10, and 13

		Straw concentration (%)				
Treatment	**Chop**	**0**	**7**	**16**	**25**	**36**
		C:N				
Week 3						
Raw feedstock	**Chopped**	n.d.	n.d.	14.0	14.5	14.5
	Unchopped		13.6	13.7	13.4	14.3
				NS	NS	NS
‡Compost piles	**Chopped**	11.5	11.7	12.4	14.6	13.7
	Unchopped		11.5	13.2	13.0	16.9
Week 6#						
Raw feedstock	**Chopped**		n.d.	13.2	13.6a	12.8a
	Unchopped	n.d	12.5a	12.9	12.8ab	12.9a
				NS	NS	NS
Pre-composted feedstock	**Chopped**	12.2	11.4b	12.3	12.3ab	11.2b
	Unchopped		13.1a	13.4	11.9b	12.5a
			**	*	NS	**
LSD across treatments (p<0.05)			0.8	NS	1.4	1.3
‡Compost piles	**Chopped**	11.0	11.6	11.5	12.1	12.3
	Unchopped		10.8	11.7	11.7	13.3
Week 10						
Pre-composted feedstock	**Chopped**	12.9	11.0	12.1	11.3	10.6
	Unchopped		13.2	12.6	12.0	11.4
			**	NS	NS	NS
‡Compost piles	**Chopped**	9.3	9.9	10.3	11.1	10.2
	Unchopped		10.3	11.0	10.8	11.7
Week 13						
Pre-composted feedstock	**Chopped**	12.2	n.d.	12.4	n.d.	10.9
	Unchopped		12.5	13.5	11.7	10.8
				NS		NS
‡Compost piles	**Chopped**	10.2	9.8	10.5	11.3	10.3
	Unchopped		9.8	11.0	12.0	10.9

#Week 6 means in the same column followed by different letters are statistically different (p<0.05).
*** indicates significant difference between chopped and unchopped levels of straw at p<0.01, * at p<0.05,* NS *not significant (p>0.10).* n.d. *indicates no data.*
‡Piles were not replicated and cannot be statistically compared to vermicompost treatments or between chop levels.

The high C:N ratios of the 25% and 36% piles was possibly due to leaching of moisture and consequent N loss at each watering event. Vermicomposting bins were sealed with lids and not aerated, thus inhibiting evaporation and leaching. Because straw did not readily absorb moisture during watering events, piles with high straw content may degraded more slowly than piles with low straw content. This is further supported by a slower rise in temperature in high-straw content piles.

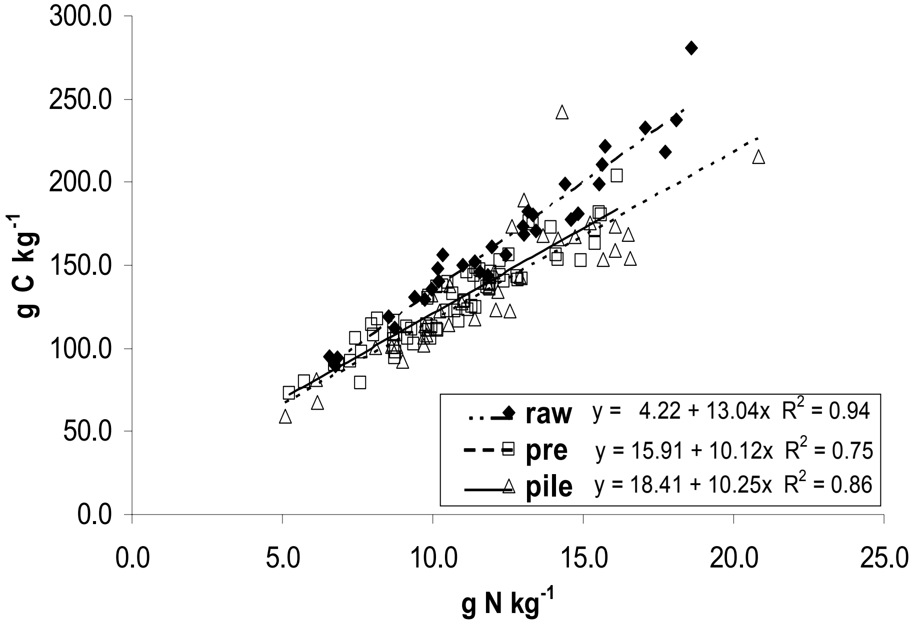

Figure 3.2: Carbon and nitrogen concentration in raw feedstock vermicompost, pre-composted feedstock vermicompost, and compost pile treatments.

A regression of C versus N concentrations in raw feedstock, pre-composted feedstock, and pile compost treatments suggested that C concentrations increased at a greater rate with increasing N concentration in raw feedstock treatments than in compost piles or pre-composted feedstock treatments ($p<0.01$) [Figure 3.2]. This was likely due to the large amounts of undigested straw in the feedstock. In the other two composting treatments, lower C concentrations suggest higher rates of C degradation. Concentrations of N and C in pre-composted feedstock were within a lower range than the other two treatments. By the time sampling of pre-compost treatments began at Week 6, a considerable amount of C had already been respired during the thermophilic phase of decomposition in the piles. As a result, the range of C and N concentration is smaller than in the other two treatments. Lower R^2 values for pre-compost and pile treatments can be attributed to differences between chopped and unchopped treatments at higher levels of straw [Figure 3.4]. A regression comparing C:N ratio to C concentration revealed a slight difference ($p<0.10$) between raw feedstock and the other two treatments, also suggesting that high C:N at a given level of C was due to lower levels of N [data not shown]. A similar regression of C:N versus N showed no difference between treatments ($p>0.10$), implying that N was consumed at the same rate in all treatments [data not shown].

3.4. Conclusion

Overall, there was little difference in final product between vermicomposting and composting. The vermicomposting bins were not optimal, nor representative of what a commercial vermicomposter would use, nor was the finished product representative of a quality vermicompost. An improved design would include drainage holes on the bottom to prevent the accumulation of water and consequent anaerobic activity. Clearly, the palatability of the straw was a major constraint in the experiment. The worms' preference for manure was demonstrated by the fact that the straw had returned to the surface by each sampling date, impeding consistent sampling techniques and increasing variability.

Because earthworms consume the mesophilic bacteria involved in the decomposition of the substrate rather than the substrate itself (Senapati, 1993a), coarse materials cannot be degraded in the earthworm gut until initial microbial degradation. The high cellulose and lignin fractions present in straw certainly slowed this decomposition considerably (Eiland *et al.*, 2001). We can conclude that the inclusion of coarse organic matter in a vermicomposting feedstock requires a considerably longer period of vermicomposting. Future researchers can consider this when determining sampling schedule and sampling may be limited to later dates when coarse material is more thoroughly and evenly integrated into the substrate. At the experimental site, worms degraded a similar mixture of pig manure and Bermudagrass (*Cynodon dactylon*) hay in a storage bin over four months, producing a fine, granular vermicompost. Finer chopping can also speed this process. However, this requires a greater investment of labor and time in a commercial production scenario. Straw visibly degraded much more readily in the compost piles compared to vermicomposting treatments in this experiment. While a dry weight straw content of 36% did not reach a C:N ratio that would inhibit composting, it was difficult to maintain sufficient moisture in piles to obtain optimal temperatures.

Composting and vermicomposting are feasible means of recycling animal and forage waste, but differ in the amount of time and labor required. Ultimately farmers must discern the marketability of the two products to determine which method suits their operation. If farmers have access to high-end gardening and organic transplant markets, vermicompost production may prove profitable despite high labor demands. If a farmer invests time and capital in attractive packaging and direct marketing, even small-scale production can be highly profitable. If management of large quantities of waste is the priority and labor availability is limited, however, large-scale windrow composting may be an easier, less labor- and capital-intensive option. In both cases, these relatively simple technologies can provide farmers the opportunity to earn value-added revenue from recycling agricultural waste.

Chapter 4: Integrating poultry litter compost and a crimson clover cover crop in organic sweet corn production on two North Carolina Ultisols

4.1. Introduction

Organic vegetable production requires non-synthetic sources of fertility in order to adhere to national organic standards. Many producers utilize amendments such as soybean (*Glycine max*) meal or feather meal for nitrogen (N), while others incorporate heavy rates of compost prior to planting. In an effort to reduce off-farm inputs, however, many organic growers incorporate N-fixing leguminous cover crops such as clover (*Trifolium* spp.), vetch (*Vicia* spp.), soybeans, or cowpeas (*Vigna unguiculata*) into their rotations to provide N to crops. While many growers who use leguminous cover crops also amend soil with compost to improve physical properties or provide a top-dressing of N for vegetable crops later in the season, there has been little research on the integration of compost and cover crop use.

4.1.1. Compost in sustainable crop production

Composted organic materials such as crop and tree residue, livestock manure, and municipal solid waste (MSW) are widely used as a soil amendment in organic vegetable crop production. Compost has been shown to improve both physical and chemical properties of soil, largely due to high quantities of organic matter (OM). Polysaccharides and other polymeric substances present in the OM act as aggregating cements (Masciandaro *et* al., 2000). Since a composted MSW may contain more than 50% OM, an application of 33.6 Mg ha^{-1} (a 1 cm thick layer) can result in an increase in humic aggregates. The resulting increase in number of small pores can improve the water-holding capacity of a mineral soil by 5 to 10%, and decrease bulk density (McConnell *et al.*, 1994). Several studies have reported increased OM, decreases in bulk density, and increased porosity in compost amended soils (Bulluck *et al.*, 2002; Debosz *et al.*, 2002; Evanylo and Sherony, 2002; Gonzales and Cooperband, 2002) compared to non-amended soils. Increases in humic matter also raise the cation exchange capacity (CEC) of amended soils, thereby lowering leaching potential of positively-charged nutrients (Bernal *et al.*, 1998b; Bulluck *et al.*, 2002). Additionally, elevated humic matter can contribute to a liming effect on soils and reduce damage incurred by aluminum toxicity in certain soil types (Molokobate and Haynes, 2002). Increased populations of beneficial microbes naturally present in or inoculated into compost can lead to general suppression or biological control of plant pathogens (Mazzola *et al*., 2002). Beneficial bacteria may outcompete pathogens for resources or produce antibiotic chemicals detrimental to a pathogen's viability (Stone, 2002). Additionally, the presence of plant growth promoting rhizobacteria (PGPR) may lead to increased incidence of induced systemic resistance (ISR) to disease (Liu *et al*., 1995; Wei *et al*., 1996; Chen *et al*., 2000).

Rates of compost application depend on the rate at which organic N is mineralized. While the North Carolina Division of Agriculture & Consumer Services (NCDA & CS) uses an N availability coefficient of 40% for broadcast compost and 50% for incorporated compost (personal communication), some researchers and farmers have determined more modest rates of mineralization. Eghball (2000) observed 11% mineralization of organic N in a beef cattle feedlot manure compost applied to a corn field the previous autumn. Mineralization was similar in both conventional and no-till systems. In a similar experiment, beef feedlot compost N availability was 20% (Eghball and Power, 1999a). The same authors reported that compost applications based on P requirements for a corn crop (supplemented with fertilizer N) resulted in similar yields to an N based application, but after four years, soil available phosphorus (P) was significantly less (Eghball and Power, 1999b). Mamo *et al*. (1998) applied 0, 44.8, 89.7, and 179.4 Mg MSW compost ha^{-1} to two different soils (sandy mixed, udothentic Haplaboroll and coarse-loamy mixed udic Argiboroll). Two other MSW composts were applied at a rate of 89.7 Mg ha^{-1}. In the composts with lower carbon to nitrogen (C:N) ratios, approximately 8% of compost N was available in the first year, whereas the compost with the higher C:N immobilized soil N and reduced corn stands. After two to three years, plant available N ranged from 3 to 10% of total compost N per year. Maynard (2002a) noted that compost N levels early in the season are often insufficient for sweet corn production requiring 146 to 179 kg ha^{-1}.

The high rates of compost required to provide fertility for organic production may raise the concern of P or heavy metal accumulation s in soils. Many growers have expressed concern with increasing metal concentrations following several years of poultry and swine manure application (Kpomblekou *et al*., 2000; Mikkelsen, 2000; Sims and Wolf, 1994; King *et al*., 1990). One study of a clay-loam calcareous soil (Fluventic Xerochrept) amended with municipal solid waste (MSW) compost over six years revealed a significant increase in Cu, Zn, and lead (Pb), as well as in chromium (Cr) in the last two years (Gigliotti *et al*., 1996).

Corn uptake of Pb was three times greater in amended soils than in an unamended control. Uptake of Cu, Zn, and Cr was twice as much as in the control.

4.1.2. Cover crops in sustainable agriculture

Due to their ability to fix atmospheric nitrogen, leguminous winter cover crops (such as clovers and vetches) are commonly used by organic farmers to fulfill the N requirements of a summer crop. Increased organic N and carbon (C) are generally associated with higher soil microbial and microfaunal populations (House and Rosario-Alzugaray, 1989; Kirchner *et al*., 1993). Added benefits include improved soil aggregation, water infiltration and rainfall retention, thereby reducing erosion (Langdale *et al*., 1987; McVay *et al*., 1989). Decker *et* al. (1994) reported above ground biomass of hairy vetch (*Vicia villosa*) in the US Coastal Plain averaged 205 kg N ha^{-1} while crimson clover (*Trifolium incarnatum*) averaged 170 kg N ha^{-1}. Biomass N accumulation was 40% less in the Piedmont. Crozier *et al*. (1994) found that crimson clover shoots may contain up to 134 kg N h yr^{-1}, while Oyer and Touchton (1990) reported a fertilizer equivalent of up to 159 kg N ha^{-1} in a crimson clover-corn (*Zea mays*)-soybean rotation. Nevertheless, a grass-legume biculture has been shown to more effectively capture residual soil N following summer droughts common to the Southeastern US due to the scavenging ability of deep-rooting grasses (Ranells and Wagger, 1997). In addition to occupying different niches in the soil profile, a mixed grass-legume winter cover crop also reduces the risk of insufficient fertility if a legume stand is stunted by a dry season or disease.

Early kill of a legume cover crop will reduce the amount of biomass N accumulation, while late kill can result in an accumulation of structural carbohydrates and lignin which will result in slow mineralization and release of plant available N (PAN). Wagger (1989) reported a 41% increase in crimson clover dry matter (DM) and a corresponding increase in total N of 23% over a treatment killed two weeks prior. However, in both years of the study, late-killed clover N was mineralized much more slowly. Ranells and Wagger (1992) evaluated the release of crimson clover N at four stages in development: late vegetative, early bloom, late bloom, and early seed set. Averaged over two years, N concentrations in clover DM declined 30%, while cellulose concentration increased by 66%, hemicellulose by 37%, and lignin by 87%.

Generally, net mineralization occurs when the C:N is less than 30 (Wagger, 1989; Ranells and Wagger, 1997), however, rates of mineralization are largely dependent on soil moisture (Ranells and Wagger, 1992). Additionally, tillage leads to a more rapid degradation of cover crop residue. Crozier *et al*. (1994) measured potentially mineralizable N pools of 170 to 255 kg N ha^{-1} in tilled crimson clover treatments, greater than levels of 117 to 210 kg N ha^{-1} in no-till and strip-till clover and conventional tillage with fertilizer in the Piedmont of North Carolina.

4.1.3. Integrating cover crops and compost

While the use of either compost or a cover crop as a fertility source in crop production is well researched, studies evaluating the integration of the two are rare. Compost added to an incorporated or unincorporated cover crop may sustain the initial flush of microbial activity and mineralize N over a longer period of time. Conversely, excess labile cover crop N may aid in mineralizing additional organic N in mature compost (Sanchez *et al*., 2001). Research at the University of California at Davis has shown significant increases in soil microbial biomass and crop yield when compost is added prior to cover crop incorporation, ultimately sustaining the microbial populations present during the first six weeks of decomposition (Humpert, 2000). Maynard (2002b) integrated leaf compost and hairy vetch in sweet corn production to reduce fertilizer requirements. Corn ear characteristics (mean weight, length, and number of rows) were not affected by vetch. Yields of two cultivars (Native Gem and Lancelot) were significantly greater in vetch + compost (112 Mg DM ha^{-1}) + fertilizer (146 kg ha^{-1} 10-10-10) than fertilizer controls, but not significantly different from compost + fertilizer treatments. Vetch biomass N and compost N were not reported. Eriksen *et al.* (1999) reported that DM and total crop N of a cereal rye (*Secale cereale*) winter cover increased linearly with compost applications of 0, 63, 126, and 189 Mg ha^{-1} and fertilized at rates of 0, 168, 336, 504, and 672 kg N ha^{-1}. In the second year, corn DM, total plant N, yield, and grain N increased linearly with the compost rates due to an increasing level of PAN as the compost mineralized. Sanchez *et al.* (2001) conducted on site and laboratory incubations of soil, red clover (*Trifolium pratense*), and composted dairy manure to determine net N mineralization of the amendments in soils either monocultured with corn or managed under a diversity of residues. After 150 days, laboratory incubations of 5 Mg ha^{-1}

clover and 5 Mg ha^{-1} compost resulted in a synergistic effect and mineralized more N than the sum of the amount mineralized by each. The researchers suggested that the high level of labile N in the clover could have enhanced mineralization of the compost. Astier *et al*. (1994) reported improved yield of broccoli (*Brassica oleracea italica*) in soils amended with 9 Mg poultry manure compost ha^{-1} + 3.6 Mg woolypod vetch (*Vicia dasycarpa*) ha^{-1} over compost or vetch alone.

The objectives of our study were to evaluate differences in N mineralization in soil amended with a crimson clover cover crop, compost, or cover crop + compost, and the subsequent effect on sweet corn growth and yield. We hypothesized that a synergistic effect would occur when the clover cover crop was integrated with a compost amendment, revealing greater and more sustained N mineralization and subsequent plant growth.

4.2. Materials and Methods

4.2.1. Experimental sites

The experiment was conducted at two sites in North Carolina—the organic unit at the Center for Environmental Farming Systems (CEFS) in Goldsboro (35.44 N 78.09W), and the Sustainable Farming Land Lab at Central Carolina Community College (CCCC) in Pittsboro (35.72N 79.18W). Soils at the Goldsboro site are Wickham series (fine-loamy, mixed, semiactive, thermic Typic Hapludults), a common soil in the eastern North Carolina coastal plain. Soils at Pittsboro are Georgeville series (fine, kaolinitic, thermic Typic Kanhapludults), common in the central North Carolina Piedmont [Table 4.1].

Table 4.1: Baseline soil data from Goldsboro and Pittsboro, October 2002

Site	Sand	Silt	Clay	HM	BS	CEC	Ac	pH	P	K	Ca	Mg
	---------------------- %					- cmol kg^{-1} -			--------------- kg ha^{-1} ------------			
Goldsboro	69.7	22.8	7.5	1.21	79.0	7.0	1.5	5.9	670	360	1,456	358
Pittsboro	26.1	60.3	13.6	0.83	91.7	10.5	0.9	6.6	10	391	2,394	766

Plots measured 6.1 m x 6.1 m each at Goldsboro, and 9.6m x 3.6m at Pittsboro, with between row spacing of 76 cm. Plots were randomly assigned to one of four treatments: cover crop (clover), banded poultry litter compost (compost), cover crop + banded compost (mix), and a fallow “control” without cover crop or compost, but fertilized with soymeal (soymeal). Treatments were replicated four times at Goldsboro and three times at Pittsboro in a randomized complete block design. Both sites were under uniform management for several years prior to our experiment: the field at Goldsboro had been fallow pasture for ten years, and was then planted with a soybean in 2002 prior to the experiment. Pittsboro plots were under pasture for fifteen years, then tilled intensively for weed control every three weeks for the last three growing seasons and cropped solely with winter grasses. Soil temperature and precipitation data during the course of the experiment was obtained from the State Climate Office of North Carolina (Raleigh, NC). Pittsboro climate measures were taken at the Siler City airport (35.69 N 79.5W, 24 km from Pittsboro plots) and Cherry Research Station (35.44 N 78.09W, 1 to 2 km from Goldsboro plots).

Table 4.2: Analysis of compost, soymeal, and crimson clover prior to incorporation, April 2003

Site	**CN**	**C**	**N**	**P**	**K**	**Ca**	**Mg**	**S**	**Fe**	**Mn**	**Zn**	**Cu**	**B**	**Na**
							mg kg^{-1}							
						Compost								
Both	8.1	280.2	17.1	8.6	6.0	29.8	2.7	7.9	3.2	0.3	0.3	*	*	4.1
						Soymeal								
Both	6.2	478.5	77.6	6.5	21.8	3.9	3.4	2.3	0.1	0.1	0.1	*	*	0.5
						Crimson clover								
Goldsboro	11.4	425.6	37.2	3.7	30.7	11.0	3.4	1.4	8.2	4.6	3.9	1.0	3.1	1.3
Pittsboro	9.2	407.3	44.1	2.6	30.7	13.5	4.1	2.1	28.9	9.5	3.8	1.1	2.9	0.3

*< 0.1mg kg^{-1}

4.2.2. Plot preparation and planting

All plots at Goldsboro were disked in October 2002, and rotovated at Pittsboro. Plots at Goldsboro were drilled on 16 October 2002 with crimson clover (*Trifolium incarnatum* cv. Dixie) at a rate of 37 kg ha^{-1} with a 2055 Sukup no-till drill (Sukup Mfg. Co., Sheffield, IA[1]). At Pittsboro, clover was broadcast at the same seeding rate with an EarthWay 3400 hand-held seeder/spreader (EarthWay Products, Bristol, IN) and incorporated manually with a rake on 19 October 2002. Soymeal and compost plots remained fallow at both sites until the following spring. On 3 April 2003, cover crop N was determined two days prior to mowing by harvesting representative above-ground clover biomass from two 0.5 m^2 quadrats in each block. Samples were dried for 2 days at 41ºC and weighed to determine biomass. Ground sub-samples were analyzed for total N by the NCDA & CS lab using the combustion method. Clover at Pittsboro was then hand-cut to 3 cm with a sickle, and mowed with a John Deere 360 flail mower at Goldsboro. A poultry litter compost purchased from a commercial

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[1] Mention of a registered trademark does not imply endorsement by North Carolina State University

producer (Green Chicken, LLC, Matthews, NC) was analyzed for total C,N, P, K, Ca, Mg, S, Fe, Mn, Zn, Cu, B, and Na using ICP-emission spectroscopy by the NCDA & CS Agronomic Division lab in Raleigh, NC [Table 4.2]. Amendment rates assumed 20 percent availability of compost N and 75 percent availability of clover N.

Due to heavy rains, amendment with compost and soymeal was delayed until five days following clover kill. A band of compost 30 cm wide was applied to each row in compost plots at a rate of 44.8 Mg ha^{-1} (within band) at both sites. Mix plots received 13.5 Mg ha^{-1} (within band) at Goldsboro and 15.7 Mg ha^{-1} (within band) at Pittsboro. Based on total clover-N and compost-N measurements, clover, compost, and soymeal plots were amended with soybean meal at incorporation to equalize treatments at a total N rate of 159.9 kg ha^{-1} [Table 4.3]. All treatment plots were disked at Goldsboro and roto-tilled at Pittsboro on 15 April 2003. Untreated yellow sugar-enhanced hybrid sweet corn (*Zea mays* cv. Early Choice; SeedWay, Inc., Elizabethtown, PA) was planted at a rate of 86,485 seeds ha^{-1} with an Almaco "jab planter" (Allan Machine Co., Nevada, IA) at Pittsboro on April 16, 2003, and with a Monosem 4-row vacuum seeder (ATI, Inc., Lenexa, KS) at Goldsboro on April 21, 2003, following field conditioning. Spacing between seeds was 15 cm and 75 cm between rows. Plots were mechanically cultivated at Goldsboro and manually cultivated at Pittsboro weekly.

Table 4.3: Source and rate of N applied to each treatment

Treatment	**Compost***	**Clover**	**Soymeal**
	-------------------------------- N (kg ha^{-1})-------------------------------		
		Goldsboro	
Clover	--	125	33
Compost	110	--	47
Mix	33	125	--
Soymeal	--	--	157
		Pittsboro	
Clover	--	113	44
Compost	101	--	56
Mix	45	113	--
Soymeal	--	--	157

*Compost rate reflective of N applied to 30 cm band
Rates assume 20% availability of compost N and 75% availability of soymeal N and clover N)

4.2.3. Soil and plant sampling

Baseline composite soil samples were taken from each block site prior to sowing of cover crops in October 2002 and analyzed by the NCDA & CS [Table 4.1]. Soil samples were taken from each plot immediately prior to incorporation of cover crop, after planting, and 2, 4, 6, 8, and 10 weeks after planting (WAP). Eight soil cores were taken to a depth of 15 cm (from a "zig-zag" pattern) in each plot and combined for a composite sample. Soils were air-dried, ground, extracted with KCl, and analyzed for soil inorganic N (SIN = ammonium-N + nitrate-N) (Keeney and Nelson, 1982) on a QuikChem 8000 automated ion analyzer (Lachat Instruments, Loveland, CO). Because emergence was poor, gaps between plants in Pittsboro were manually reseeded 3 WAP. At 5 WAP, three representative plants from the four middle rows of each 8- or 10-row plot were measured for height and cut 3 cm above the soil surface. To avoid bias due to competition, plants were not sampled from adjacent positions within rows. Plants were composited for each plot to determine biomass (DM). Pooled samples were oven dried for 48 hours at 60ºC, weighed, and ground to 1 mm for total N analysis in a PerkinElmer 2400 CHN/O analyzer (PerkinElmer, Boston, MA). Mean plant height was determined from 10 representative plants in each plot at both 5 and 7 WAP. Whole plots were harvested on 28 June 2003 in Goldsboro and on 2 July in Pittsboro by manually cutting all plants at 3 cm above soil surface and removing biomass from the sample area. Plants were counted to determine harvest density and weighed to determine total fresh weight biomass. Ears were removed from the plants, categorized as marketable (>15 cm) or non-marketable (<15 cm) [Figure 4.1], counted, and weighed.

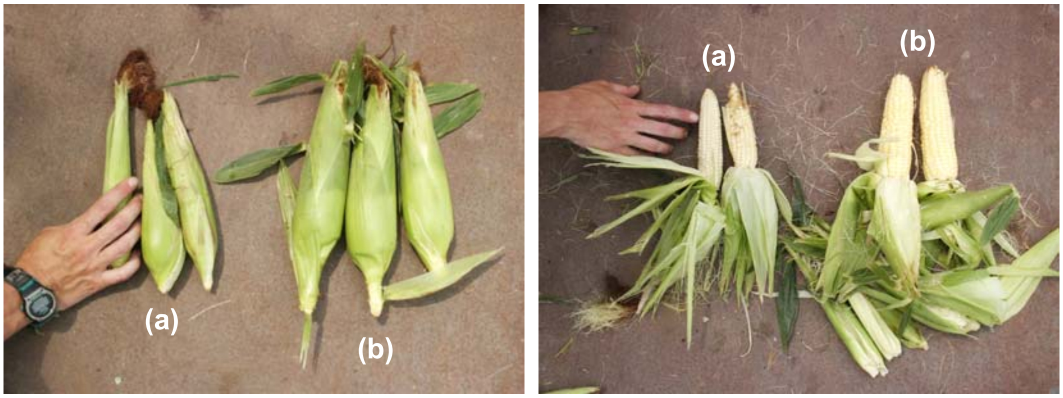

Figure 4.1: Comparison of (a) non-marketable and (b) marketable ears

A representative sub-sample of three plants was weighed in field, then oven-dried for 48 hours at 60ºC, weighed to determine dry matter content, ground, and analyzed for total N concentration as described above. All data was analyzed using PROC GLM, ANOVA regression analysis, and LSD contrast (SAS Institute, Cary, NC).

4.2.4. Determining residual N uptake

At Pittsboro, all plots were cleared of sweet corn residue, roto-tilled ten days after harvest, and seeded with pearl millet (*Pennisetum glaucum*) on 22 July using the Earthway hand seeder. At Goldsboro, plots were cleared of residue, and German foxtail millet (*Setaria italica*) was planted at a rate of 22.4 kg ha^{-1} using a Sukup 2055 no-till drill 9 days after corn harvest. Two 0.5 m^2-quadrats were placed randomly within each plot and millet was harvested at a height of 2 cm at 4 WAP, dried, weighed, ground, and analyzed for total biomass N. Harvest uptake efficiency (HUE), a measure of N use efficiency, was calculated as percent recovery of applied N, where efficiency equals the ratio of total crop N at harvest to total applied N (Moll, *et al*, 1982).

$$\text{HUE} = (\text{total N of plant at maturity}) / (\text{total N applied}) \times 100$$

4.2.5. Lab incubation

Soil was sampled at both sites from control (soymeal) plots in early April 2003 prior to soymeal application and sieved with a 2 mm mesh to separate coarse material. Screened samples were spread on paper and allowed to air-dry for several days. Four 100 g sub-samples of each soil were brought to saturation and weighed to determine soil wet weight. Field capacity was adjusted to 60% saturation. Twelve 3.8 L, thin-walled resealable plastic bags were filled with 662 g of dry soil from Pittsboro, and twelve bags with 769 g of dry soil from Goldsboro. Bags were randomly assigned the same treatments as the field trial (clover, compost, mix, and control) and replicated three times. Three grams (3 g) of dried clover was obtained from the Pittsboro cover crop sampling, ground to 2 mm, and added to clover and mix bags. Assuming 75% availability, additions were equivalent to 5 Mg DM ha^{-1}, or 150 kg N ha^{-1} as plant available N (PAN). Air-dried compost was manually ground and sieved to 2 mm and 23 g added to compost and mix bags (62.8 Mg compost ha^{-1}, ~150 kg PAN ha^{-1} at 20% availability). Amended soil was mixed thoroughly and water was added to bring all bags to equal weight of 1 kg for each bag. Bags were weighed every two weeks and watered when necessary (~5 g of water at each sampling date) to maintain consistent moisture, about 15% for soil from Goldsboro and 25% for soil from Pittsboro. Four 25 g sub-samples were taken from each bag immediately after the initial mixture and composited. Bags were sampled again at 2, 4, 6, 8, and 16 weeks. Samples were allowed to air-dry and SIN was extracted with a KCl solution as previously described. Net mineralized SIN levels were determined by subtracting levels observed in the unamended control for each soil. Clover and compost data were summed to create an aggregate data set for comparison with mix treatments. All results were analyzed using PROC GLM regression or repeated measures ANOVA with Helmert's contrasts to compare weeks (SAS Institute, Cary, NC).

4.3. Results and Discussion

4.3.1. Clover growth

Accumulation of crimson clover biomass at Goldsboro was 166 kg total N ha^{-1} and 151 kg total N ha^{-1} at Pittsboro, or 31% greater at Goldsboro than at Pittsboro, and was likely due to differences in seeding method, climate, and soil type. Stands were more uniform at Goldsboro where seed was drilled, while seed at Pittsboro was broadcast with a hand-spreader and manually incorporated with a rake. Seed-soil contact was likely superior at Goldsboro. Mean soil temperature was 1°C higher at Goldsboro while Pittsboro received 64 mm more rainfall [Figure 4.2]. Low levels of soil P may have also contributed to slower growth [Table 4.2].

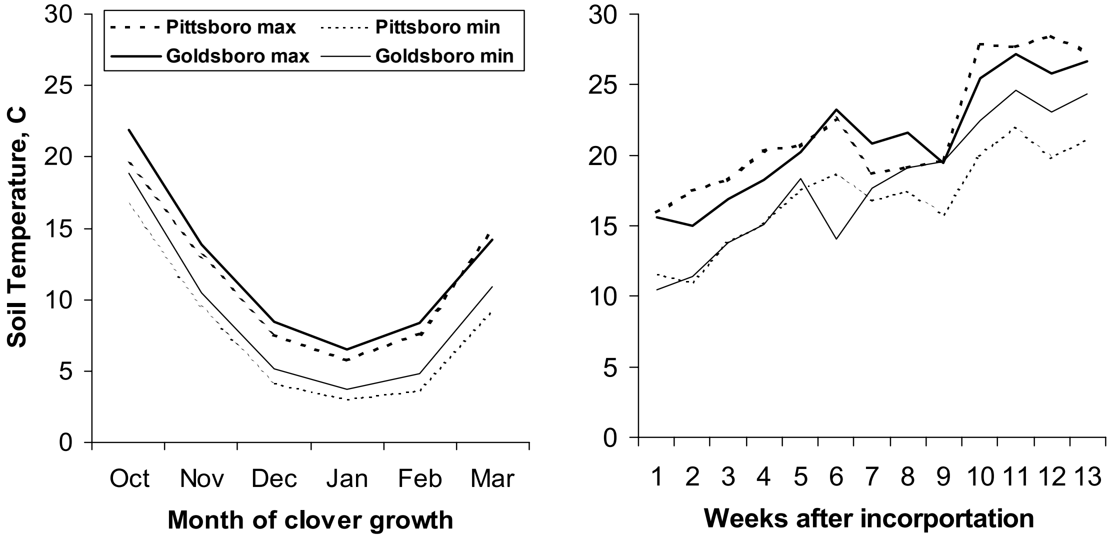

Figure 4.2: Average soil temperatures at 10 cm-depth during experiment at Goldsboro and Pittsboro sites.

4.3.2. Plant growth and yield

Emergence density and subsequent plant population of sweet corn plants was poor at both sites [Figure 4.3], most likely due to heavy rains [Figure 4.4] and subsequent low soil temperature [Figure 4.4]. Both sites received ~76 mm of rain the week of planting and soil temperature remained below 15°C. Because both sites were designated for certified organic production, untreated seeds were used, thus increasing the potential for pre-emergence seed-rot. Emergence density at Pittsboro was poor compared to the soils at Goldsboro [Figure 4.3]. Clay content of the Pittsboro soil was associated with higher available water-holding capacity (WHC) than in the Goldsboro soil, also increasing the potential for seed-rot. Additionally, precipitation in Pittsboro averaged 7 cm less and soil temperature 0.7°C lower [Figure 4.4] than in Goldsboro from 0 to 2 WAP.

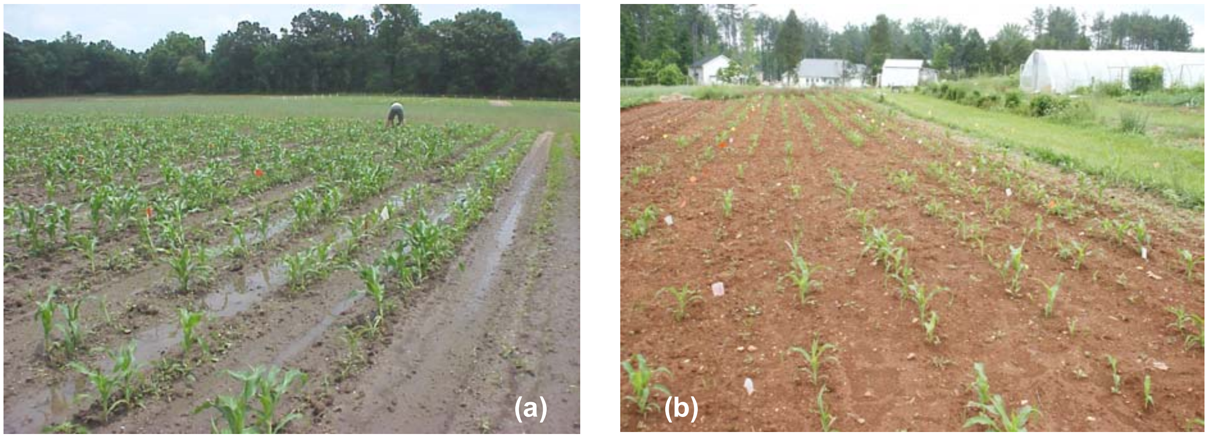

Figure 4.3: Sweet corn populations at (a) Goldsboro and (b) Pittsboro

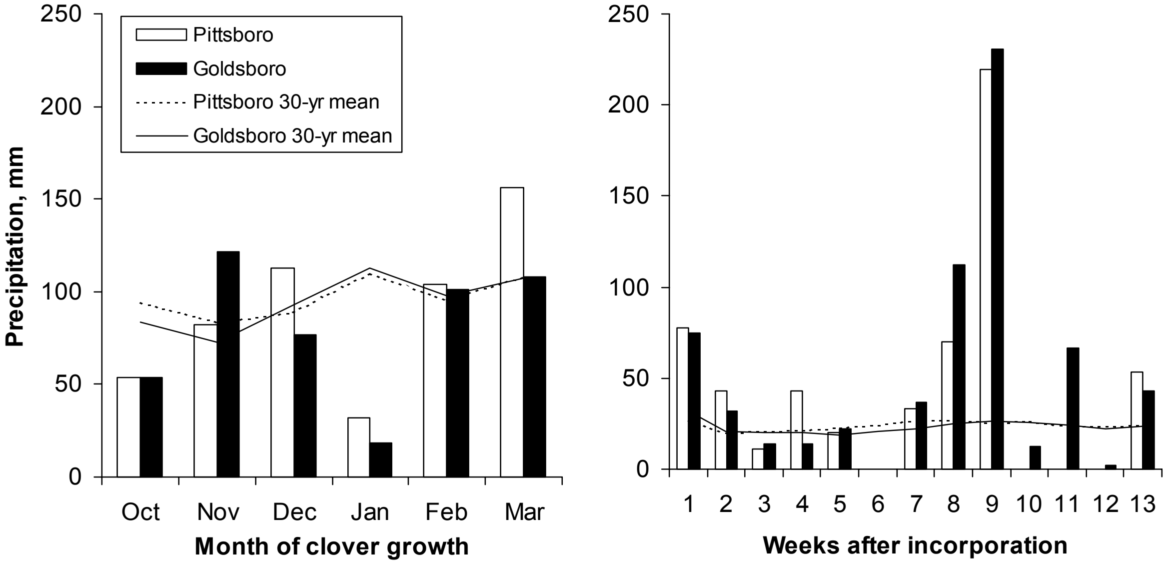

Figure 4.4: Average precipitation at Goldsboro and Pittsboro during experiment

Topographical variation in plots at both sites may have increased variance in density and plant growth measurements. Visual inspection revealed that low-lying blocks had visibly lower emergence, yet differences were generally not significant. Density at Goldsboro 5 WAP was significantly different across treatments ($p<0.0001$) [Figure 4.5]. At Pittsboro where variability was greater, treatments were not significant ($p>0.10$) at 5 WAP. Similarly, plant density at harvest was not significant ($p<0.10$). Heavy rains 5 WAP that briefly flooded ~50% of the Goldsboro plots may have resulted in lower plant density. Low levels of available P at Pittsboro may also have been responsible for poor harvest densities. P deficiency can have deleterious effects on leaf expansion, root development, and biomass accumulation in corn plants (Mollier and Pellerin, 1999). High incidence of cutworm throughout the experiment also may have led to lower population at harvest.

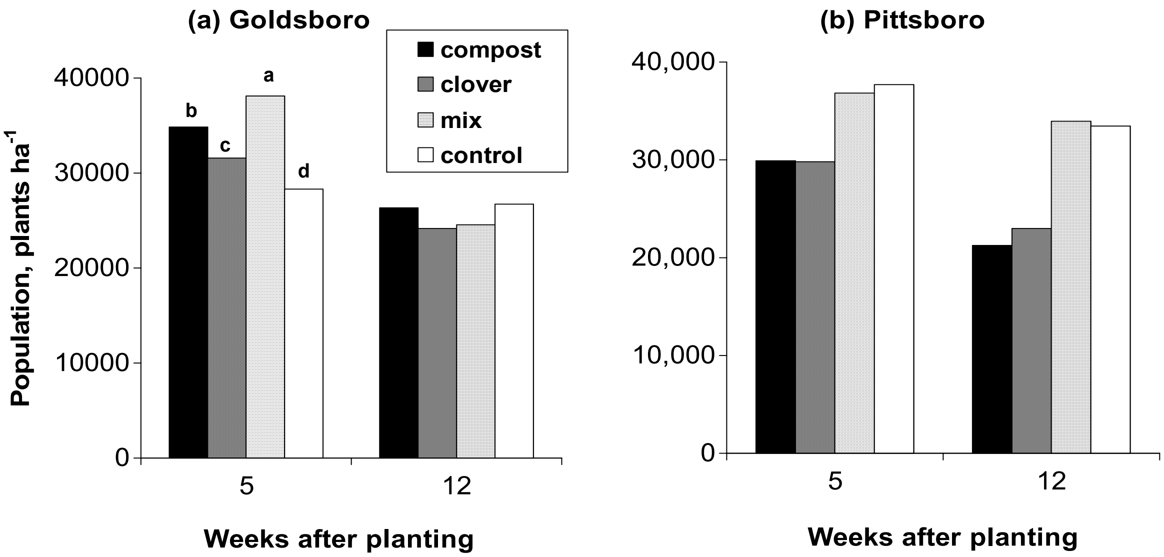

Figure 4.5: Plant population at 5 and 12 WAP at (a) Goldsboro and (b) Pittsboro. Bars with different letters are significantly different ($p<0.05$).

Plant growth may have been stunted by heavy rains 2 WAP. Flooding can lead to denitrification and subsequent N deficiency and growth reduction in corn plants (Ashraf and Rehman, 1999; Mukhtar et al, 1990). There was no significant difference in plant height between treatments at either site at either 5 or 7 WAP [Figure 4.6].

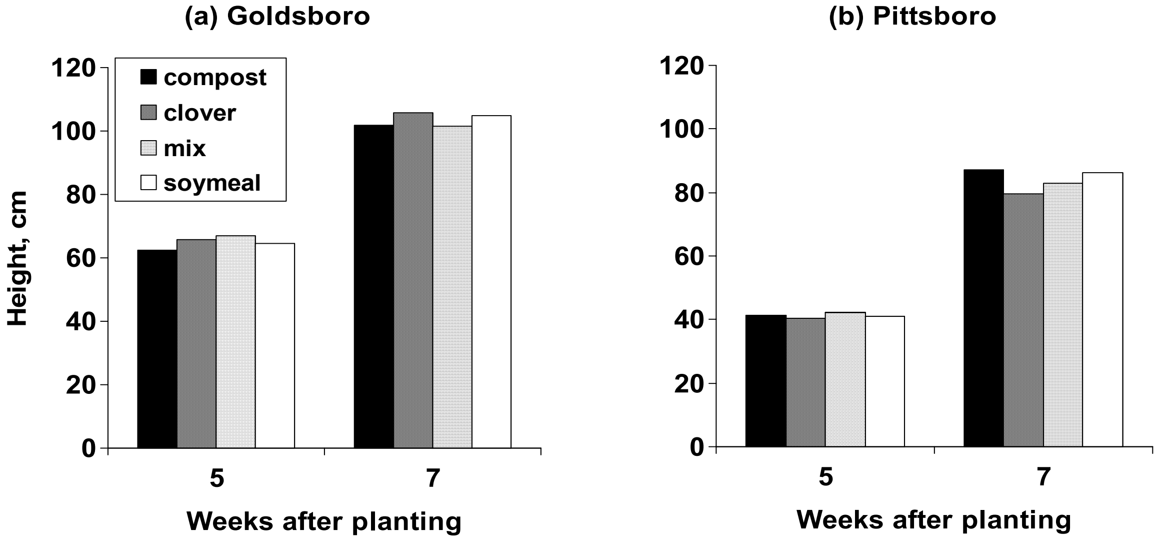

Figure 4.6: Sweet corn height at (a) Goldsboro and (b) Pittsboro at 5 and 7 WAP

At Goldsboro, mean biomass within treatments ranged from 107 to 169 kg ha^{-1} at Week 5, and did not increase significantly ($p<0.05$) by harvest (Week 12) [Figure 4.7]. Low biomass at harvest can be attributed to low populations. At Pittsboro, biomass ranged from 13 to 57 kg ha^{-1} at 5 WAP and increased to 181 to 220 kg ha^{-1} by harvest. There were no treatment differences ($p<0.05$) at either date.

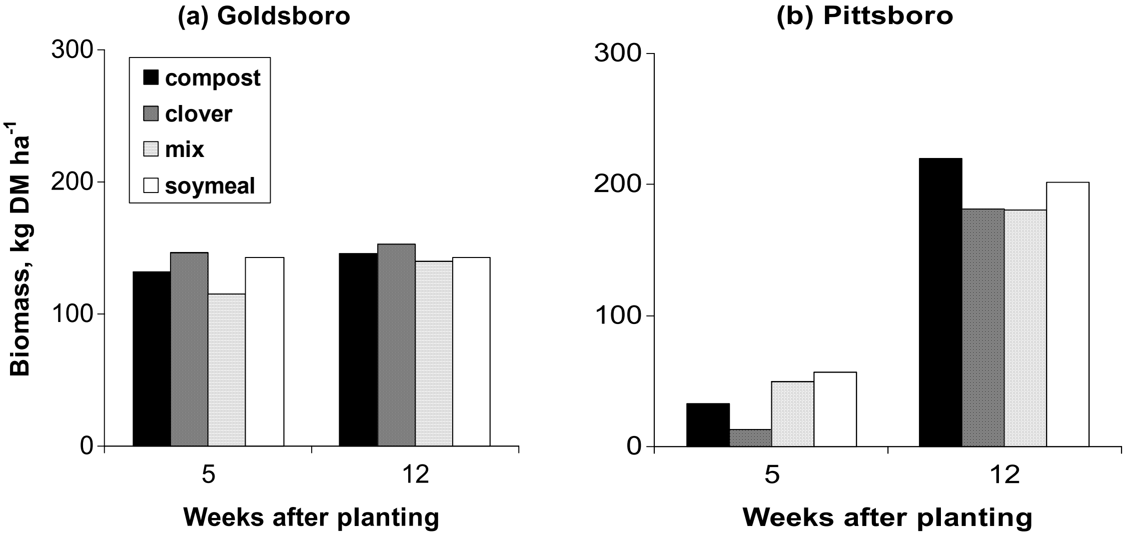

Figure 4.7: Sweet corn biomass at (a) Goldsboro and (b) Pittsboro at 5 and 12 WAP (harvest).

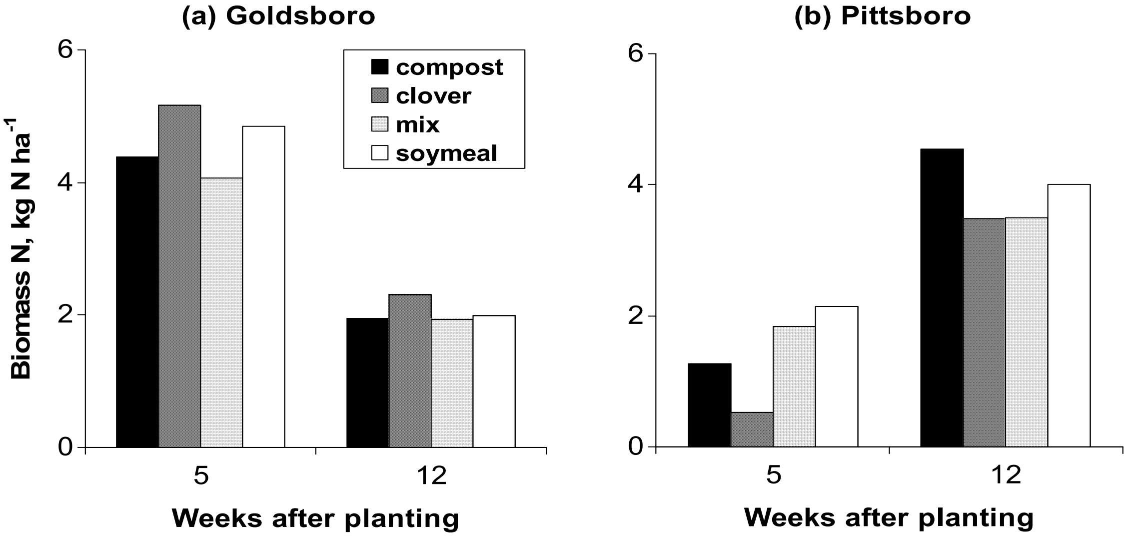

Figure 4.8: Sweet corn biomass N at (a) Goldsboro and (b) Pittsboro at 5 WAP and at harvest (12 WAP).

Total biomass N at Goldsboro decreased ($p<0.0001$) [Figure 4.8] between 5 WAP and 12 WAP and can be attributed to a reduction in total N concentration from 30 to 10 g kg^{-1} [data not shown], and to a decrease in plant populations [Figure 4.3]. Soil inorganic N decreased from 5 to 12 WAP and may have affected plant uptake. In Pittsboro, biomass N increased ($p<0.0001$) due to the increase in biomass from 5 to 12 WAP. Total N concentrations at Pittsboro decreased from 40 to 20 g kg^{-1} [data not shown]. Treatment effects were significant ($p<0.05$) when averaged over both sampling dates.

While total number of ears harvested at Goldsboro was not significant between treatments [Figure 4.9], the number of marketable ears grown in clover treatments was 31% greater than in compost and 19% greater than mix ($p<0.05$). There was no difference in marketable ears between soymeal, compost, and mix treatments, nor between clover and soymeal treatments. The higher C:N of clover (11.1) may have resulted in slower mineralization of N than soymeal (C:N = 6.2) and compost (C:N = 8.1), and less available N during corn silking and ear development (Weeks 6 to 12), when 60 to 100% of total N uptake by the plant occurs (Aldrich *et* al., 1975). Previous research has reported direct relationships between increasing C:N and decreasing rate of N mineralization from crimson clover residue (Ranells and Wagger, 1992; Wagger, 1989)

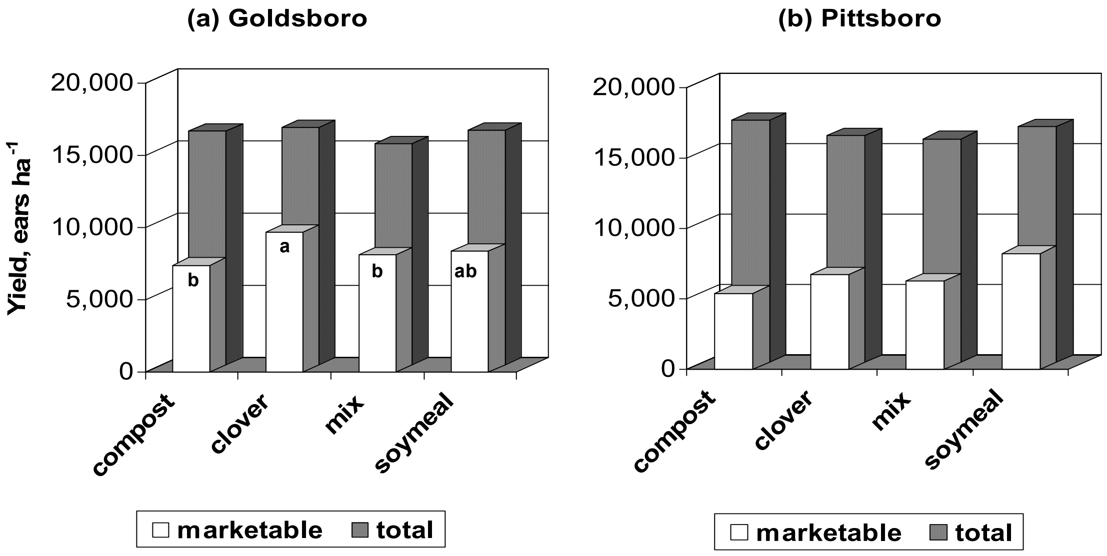

Figure 4.9: Total and marketable sweet corn yields at (a) Goldsboro and (b) Pittsboro. Bars with different letters are significantly different ($p<0.05$).

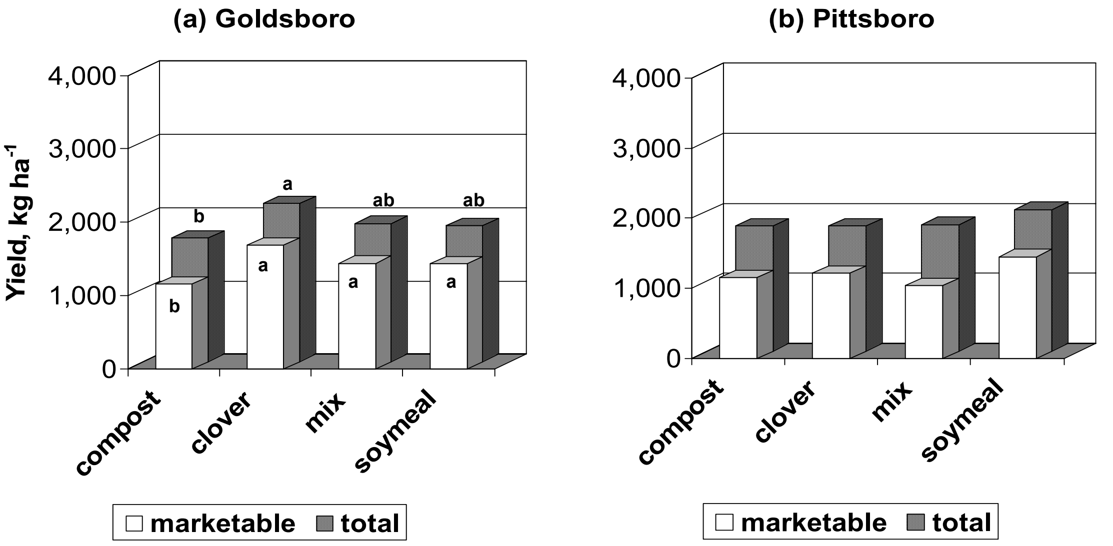

Figure 4.10: Total and marketable sweet corn yield of ears on a fresh weight basis, at (a) Goldsboro and (b) Pittsboro. Bars with different letters are significantly different ($p<0.05$).

Total yield by weight of compost plots was 22% less than clover plots ($p<0.05$), but there was no significant difference between compost, mix, and soymeal plots [Figure 4.10]. Similarly, marketable yield of compost plots was 20 to 31% less than that of the other treatments ($p<0.05$). Total and marketable yields and number of marketable ears were 22 to 32% lower ($p<0.05$) in blocks that had been flooded 5 WAP.

At Pittsboro, the average number of marketable ears ha^{-1} by treatment ranged from 5,426 (compost) to 8,247 (soymeal), with total ears per hectare ranging from 15,843 for the compost + clover treatment to 17,145 for the compost treatment [Figure 4.9]. There was no difference in yield between treatments in Pittsboro ($p>0.05$) [Figure 4.10]. The high variance can be attributed mostly to the block effect at the Pittsboro site.

4.3.3. Soil inorganic nitrogen

At Goldsboro, soil inorganic nitrogen (SIN) ranged from 7 to 12 kg N ha^{-1} at the time of amendment (Week 0) [Figure 4.11]. Compost treatment SIN was significantly lower than in mix and clover treatments ($p<0.05$) at Week 0. Mix treatment SIN was higher ($p<0.05$) than both soymeal and compost treatments while clover treatment was only higher than compost ($p<0.05$). Higher SIN levels in both clover and mix treatments can be attributed to six months of biological N fixation by the crimson clover plants. The low SIN levels in compost treatments a few days following incorporation (Week 0) may be associated with immobilization of SIN by the recalcitrant carbon fraction of compost. While the compost had a low overall C:N, it was visibly clumpy and heterogeneous.

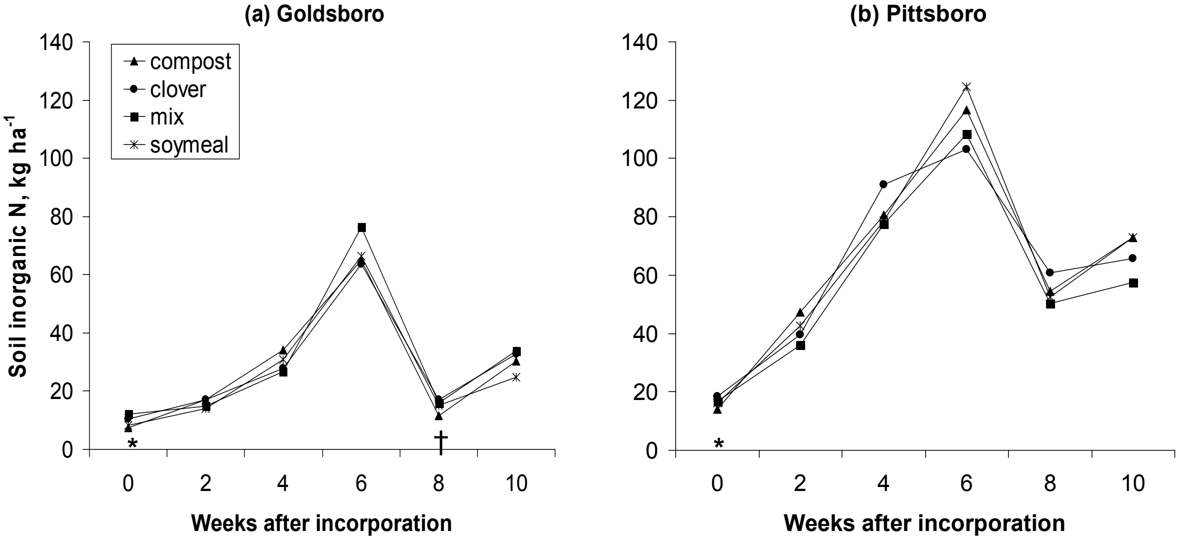

Figure 4.11: Soil inorganic N of soils cropped with sweet corn at Goldsboro (a) and Pittsboro (b) sites following incorporation of compost, clover, compost + clover (mix), or soymeal.
* indicates significant treatment effect at $p<0.05$, † at $p<0.10$.

Soil inorganic N of all treatments rose gradually until Week 4, attaining levels between 27 and 34 kg N ha^{-1}. At Week 6 levels peaked steeply at Week 6 between 64 and 73 kg N ha^{-1} (likely due to rainfall the preceding weeks) and then declined rapidly until Week 8 to levels slightly above Week 0 levels. This sudden decrease may be due to leaching associated with heavy rainfall during Weeks 7 and 8 that was three- to four-fold higher than 30-year means. During this same period, compost treatments were slightly lower ($p<0.10$) than mix and clover treatments. The drop in SIN may also be due to plant uptake during this period. Approximately 56 kg N ha^{-1} can be taken up between silking and harvest (Marr, 1994) and up to 40% of total N uptake may occur during ear development (Evans, 1995). SIN levels of all treatments rose again by Week 10 two- to three-fold.

At Pittsboro, SIN levels followed the same pattern, but rose much more steeply [Figure 4.11] from initial levels ranging from 14 to 19 kg N ha^{-1}, where compost treatment SIN levels were significantly lower than that of clover ($p<0.05$). By Week 6, levels had reached as high as 125 kg N ha^{-1}, before decreasing to ~60 kg N ha^{-1} by half over the following two weeks. Soil inorganic N levels in clover and mix treatments rose more gradually at Pittsboro than at Goldsboro between Weeks 8 and 10. Differences between treatments were not significant after Week 0. Averaged across the entire experimental period, treatment differences were not significant ($p<0.05$) at either site.

Soil inorganic N dynamics were different between the two sites ($p<0.0001$), likely attributed to differences in methods of incorporation and soil type. Rotovating of amended soil in Pittsboro likely resulted in greater disturbance and faster subsequent release of N than disking at Goldsboro (Crozier *et al*, 1994; Salinas-Garcia et al, 1997). The Goldsboro soil, with its low cation-exchange capacity (CEC) and large sand fraction, is less able to retain nutrients (Wang and Alva, 2000) during heavy precipitation than the Pittsboro soil, and a considerable amount likely leached below the root zone. This difference in adsorption capacity between the two sites may help explain the lower inorganic N levels throughout the duration of the experiment. The superior growth of sweet corn plants at Goldsboro may also indicate high plant uptake and subsequent low SIN in Goldsboro soil samples.

There were no significant differences in SIN between treatments, nor any significant interaction between compost and clover amendments. Nevertheless, marginally significant interactions were found between site and clover treatments ($p<0.10$), and site, clover, and time ($p<0.10$). These differences may be due to the slow rate of mineralization of NH_4^+ in clover and mix treatments [data not presented]. Higher precipitation and soil temperatures in Pittsboro from Week 2 onwards may have been accelerated the rate of decomposition of clover residue in mix and clover treatments compared to Goldsboro. Indeed, the high available WHC associated with the clay fraction of the Pittsboro soil likely retained a higher level of moisture in the clover residue for longer periods compared to Goldsboro. Similarly, a high sand fraction at Goldsboro liley led to faster drying due to increased pore size. As a result, microbial populations may have been more responsive in the Pittsboro soil, hastening decomposition and release of inorganic N. At Pittsboro, high ammonium concentrations in soymeal and compost treatments during the first 6 weeks following incorporation suggest enhanced microbial activity [Figure 4.10]. Soymeal (C:N = 6:2) and compost (C:N = 8.1) organic N may have mineralized more rapidly than the clover residue (C:N = 9.2 and 11.1) during the 6 weeks following incorporation due to higher C:N. Furthermore, the small particle size of the soymeal and compost may have hastened mineralization. Bending and Turner (1999) reported that microbial biomass N was 90% greater ($p<0.05$) in a sandy loam amended with finely chopped (2 mm) potato (*Solanum tuberosum*) shoots (C:N = 10) than with coarsely chopped (4 cm) three weeks after incorporation. After an additional week, there was no difference in mineralization due to particle size. Similarly, SIN at 3 weeks after incorporation of finely chopped Brussels sprout (*Brassica oleracea gemmifera*) shoots (C:N = 15) was significantly higher than coarsely chopped treatments and resulted in immobilization until Week 4.

Application of soymeal to all treatments in an effort to equalize N application across treatments may have masked treatment effects. High levels of inorganic N were likely released quickly following incorporation due to low C:N, small particle size, and high N concentration (78 g kg^{-1}). This early flush may have led to a priming effect in all treatments, rather than solely in the mix treatment as anticipated. Different carbohydrate structures in soymeal and clover may have also affected the rate of N mineralization. Research has demonstrated that combinations of plant materials with different chemical and structural composition may lead to both immobilization and mineralization of N at different stages in decomposition (Gunnarsson and Marstorp, 2002).

4.3.4. Total N recovery

Data for German foxtail millet at Goldsboro and post-millet SIN at both sites were not available due to field management oversight. At Pittsboro, pearl millet biomass in compost plots was 38% higher than in soymeal plots ($p<0.05$), and clover plot millet biomass was 40% higher than soymeal ($p<0.05$) [Figure 4.12a]. Mix treatment biomass was not different from the other three treatments ($p>0.05$). Total N concentration [Figure 4.12b] in millet grown in compost plots was 21% lower than that of mix ($p<0.05$) and 17% lower than in soymeal plots ($p<0.05$). Millet grown on clover plots was not different than other treatments ($p>0.05$).

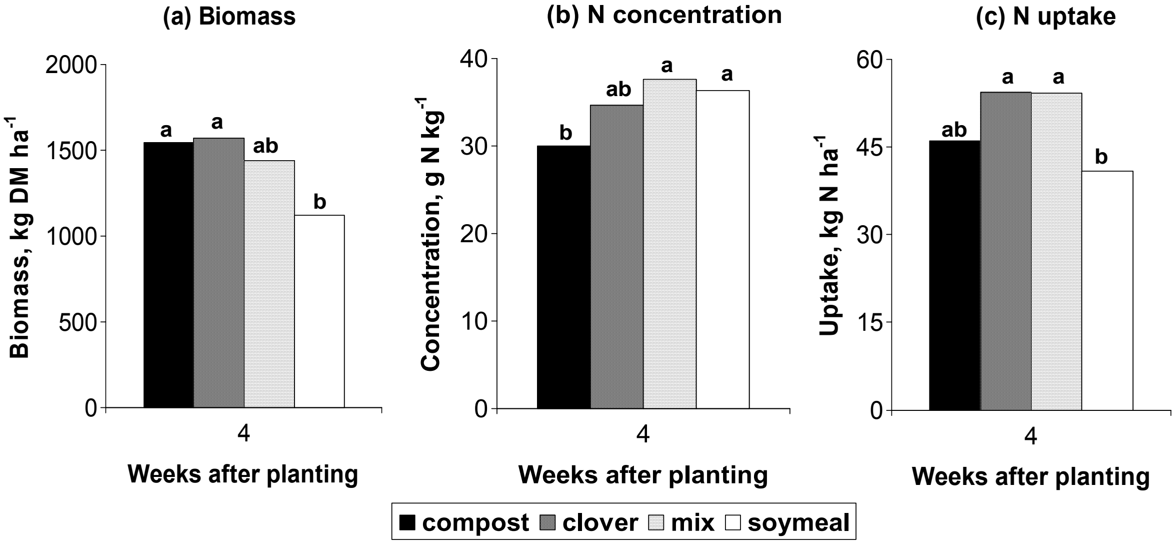

Figure 4.12: Total millet biomass (a), millet N concentration (b), total N uptake (c) at final harvest of pearl millet at Pittsboro, 19 August 2003. In each graph, bars with different letters are significantly different ($p<0.05$).

Total N uptake by the millet crop, was greatest in clover and mix treatments, averaging 27% higher than N uptake in the soymeal control plots ($p<0.05$). Total uptake from compost plots did not differ from other treatments ($p<0.05$); however, total N concentration in millet on compost-amended plots was 20% lower than in mix and 17% lower than in soymeal treatments ($p<0.05$), suggesting reduced N availability. While total N uptake in compost plots was not statistically different from soymeal plots, data revealed a trend of higher uptake from compost, clover, and mix plots. The homogeneity of soymeal may have reduced the diversity of the biologically-active community; large particle size of the compost, clover, and mix treatments may have supported greater diversity by providing different feedstocks at several trophic levels (House and Rosario-Alzugaray, 1989). In contrast, soymeal may have only been able to support microbial and fungal activity. Large microbial flushes following soymeal application have been reported in other studies (Viteri and Schmidt, 1996; Lazarovits et al, 1999; Lazarovits, 2001). Similarly, low C:N, small particle size and high protein concentration of soymeal and compost may have led to rapid mineralization early in the season. Due to higher than average precipitation, much of the nitrate may have leached before it was utilized by sweet corn plants.

Table 4:4: Total N recovery during experiment, Pittsboro

Treatment	Applied N*	Corn uptake	Millet uptake	Total uptake	Unrecovered	HUE
	kg N ha^{-1}					%
Compost	157†	4.5	46.1ab	50.6ab	106.3ab	32.2ab
Clover	157	3.5	54.3a	57.7a	99.2a	36.8a
Mix	158†	3.5	54.2a	57.6a	100.8ab	36.7a
Soymeal	157	4.0	41.0b	44.8b	112.1a	28.5b
LSD		NS	11.4	12.4	12.4	7.9
CV%		16.8	11.6	11.8	6.0	11.8

Values in the same column followed by different letters are significantly different at $p<0.05$. NS indicates not significantly different ($p>0.05$)

*assumes 20% availability of compost and 75% availability of soy meal and clover

†Applied N in compost and mix treatments based on compost rates within a 30 cm band

Overall, total N recovery (corn N + millet N) was poor in Pittsboro [Table 4.4] due to poor corn stands and reduced yields. Ranging from 3.5 to 4.5 kg N ha^{-1}, total N recovery by corn plants was considerably lower than recovery by sweet corn in other experiments due to low yields. In a study on a Malaysian Ultisol (Typic Paleudult) receiving 2100 mm annual rainfall, unfertilized sweet corn N uptake averaged 25 kg N ha^{-1} over three seasons, while sweet corn fertilized with *Glyricidia sepium* prunings containing 120 to 160 kg N ha^{-1} assimilated 36 kg N ha^{-1} in aboveground plant tissue (Zaharah *et al.*, 1999). Yields were three- to four-fold higher than in our experiment, however. Isse *et al.* (1999) reported N recovery levels of 26 and 44 kg N ha^{-1} in sweet corn crops yielding 1 to 2.7 Mg grain DM ha^{-1} grown on two Quebec soils following an incorporated of red clover cover crop. Nevertheless, N uptake was similar to both experiments. Textbook and extension literature has also noted uptake of 3.4 to 3.7 kg N Mg marketable ears^{-1} on a fresh weight basis (Marr, 1994; Nonnecke, 1989).

Poor N recovery may also be due to excessive leaching since precipitation during the growing season was considerably higher than average at both sites. Research by Hubbard *et al.* (1991) on a sandy Coastal Plain soil in Georgia showed that most nitrate in the upper 30 cm of a sweet corn crop's root zone was leached during rainfall events ≥ 200 mm, increasing N concentrations up to 19 mg L^{-1} in groundwater at 0.9 to 1.8 m depth.

Nitrogen uptake by corn + millet crops in both clover treatments was ~58 kg ha^{-1} [Table 4.4]. Uptake from soymeal plots was 23% less than from clover and mix plots ($p<0.05$), while uptake in compost plots was not significantly different. Harvest use efficiency (HUE) was significantly lower in soymeal treatments than in mix and clover treatments. Following trends observed throughout the experiment, this may be attributed to low C:N, small particle size, and high protein concentrations in the soymeal, resulting in a rapid release of PAN before efficient utilization by corn plants was possible. As N is mineralized in synchrony with growth, less N may be lost to denitrification, volatilization, or leaching. Additionally, some N may have remained in organic form. Duffera *et al*. (1999) concluded that only 10% of applied organic N in swine solids was mineralized over sixteen weeks of incubation.

4.3.5. Lab incubation

In the lab incubation, treatments that included compost exhibited significantly higher initial concentrations of SIN, suggesting elevated concentrations of inorganic N in the amendment and an underestimation of availability [Figure 4.13]. Compost and mix SIN concentrations also remained higher than treatments without compost during the incubation. In soil from the Goldsboro site, compost treatment SIN declined sharply from 49 to 28 mg g^{-1} by Week 2 and leveled off. In contrast, compost + clover (mix) treatment N, remained stable until Week 2, then increased steadily until Week 8, and slowly stabilized. Clover treatment SIN decreased slightly until slight immobilization at Week 6, before increasing more than three-fold over initial levels. In the soil from the Pittsboro site, SIN behaved differently. Compost treatment SIN increased nearly four-fold in the first two weeks, before dropping steeply to initial levels by Week 8. Clover incorporation resulted in lower SIN, perhps related to immobilization, and gradually increased until the end of the incubation. By Week 8, mix treatment SIN had decreased five-fold to 5 mg g^{-1}, and increased again by Week 16 to 16 mg g^{-1}, presumably as clover N may have become more available. Similar N dynamics were reported by Kumar *et al.* (2002) following incorporation of sugar beet (*Beta vulgaris*) processing by-products or biosolids. Biosolids resulted in net mineralization over 120 days, while the beet by-products resulted in initial N immobilization (26 to 121 mg N kg soil^{-1}), before resulting in net mineralization.

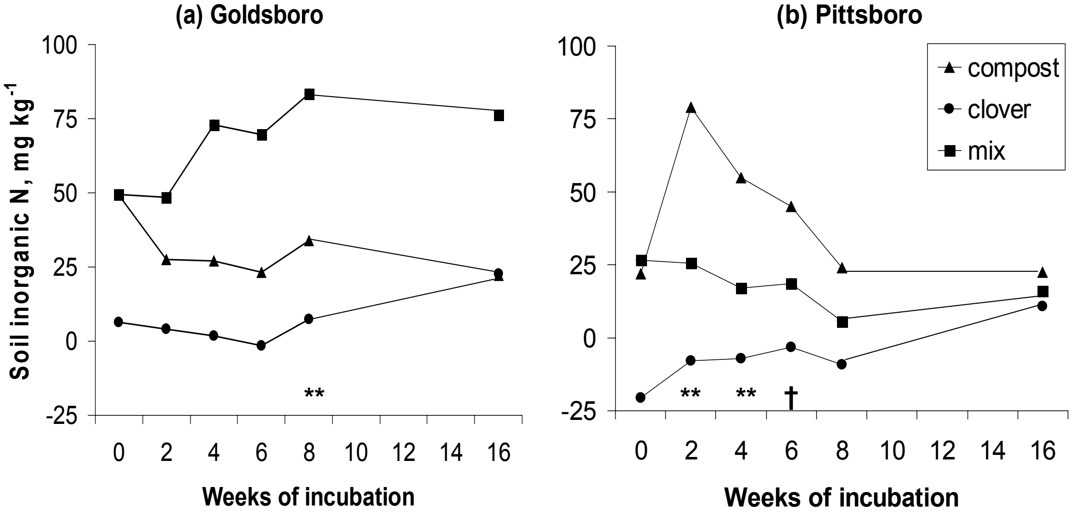

Figure 4.13: Soil inorganic N in incubated soil samples from (a) Goldsboro and (b) Pittsboro following incorporation of compost, clover, or compost + clover (mix). Treatment significance is based on Helmert's contrast of each week to the mean of subsequent weeks (** indicates significant treatment effect at $p<0.01$, † at $p<0.10$). Values represent treatment means minus control treatment values.

Using repeated measures ANOVA, a contrast of Week 0, 2, and 4 to later weeks showed highly significant treatment effects ($p<0.01$) in the Pittsboro soil. Week 6 was slightly significant ($p<0.10$). In the Goldsboro soil, treatment effects were only significant ($p<0.05$) at Week 8.

In Pittsboro, SIN levels of mix treatments were significantly lower ($p<0.0001$) than the aggregate of clover and compost treatments [Figure 4.14]. This may have been due to immobilization of compost N by clover residues and adsorption of ammonium by the clay and silt fraction of the soil (Wang and Alva, 2000). In the sandier Goldsboro soil, mix treatment SIN significantly exceeded ($p<0.01$) the sum of individual clover and compost treatments, supporting the findings of Sanchez *et al.* (2001), and suggesting a priming effect, or the mineralization of soil N due to the addition of amendment N (Brady and Weil, 2002). This increase occurred in the nitrate fraction of SIN, as mix ammonium levels decreased ($p<0.05$) below aggregate ammonium by Week 4 [data not shown].

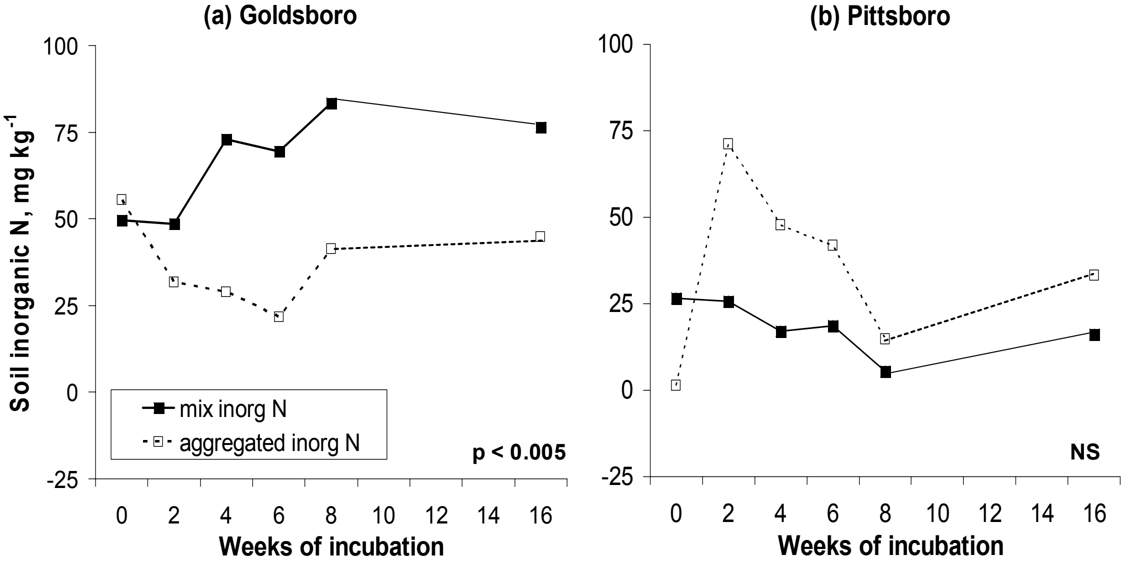

Figure 4.14: Net release of soil inorganic N (mg SIN kg soil^{-1}) following amendment with compost + clover (mix) compared to the aggregated sum of clover and compost treatment SIN. Treatment significance is averaged across duration of the experiment. Values represent treatment means minus control treatment values.

The priming effect may have been induced by the compost; C concentrations in the compost were low and perhaps less recalcitrant than those of the clover. Martín-Olmedo and Rees (1999) reported a priming effect in an incubation of a sandy loam amended with 2.4 g poultry manure kg soil^{-1} + 60 kg ^{15}N-labelled ammonium sulfate ha^{-1}. Treatments containing an additional 1.05 or 4.22 g kg^{-1}cellulose did not depict a similar result. In our field trial, application of soymeal may have induced a similar priming effect in all treatments.

Furthermore, a high sand fraction and low clay levels in the Goldsboro soil may have resulted in more rapid drying than in the Pittsboro soil. Research has related nitrate availability to the microbial flushes that occur during wetting cycles (Cabrera, 1993; McInerney and Bolger, 2000). Had watering events been more frequent or moisture remained constant, nitrate levels may have been lower. Indeed, the bi-weekly watering events may have had a more pronounced effect on bacteria that mineralize soil nitrogen than in the more clayey and consequently slower-to-dry Pittsboro soil. Gioacchini *et al.* (2002) reported a urea-induced priming effect that resulted in greater release of SIN in a sandy loam than in a clay loam.

There was no difference (p>0.05) in the proportion of SIN in the Goldsboro soil released during the incubation to the amount of total N applied as organic amendments (compost, clover, or compost + clover) [Figure 4.15].

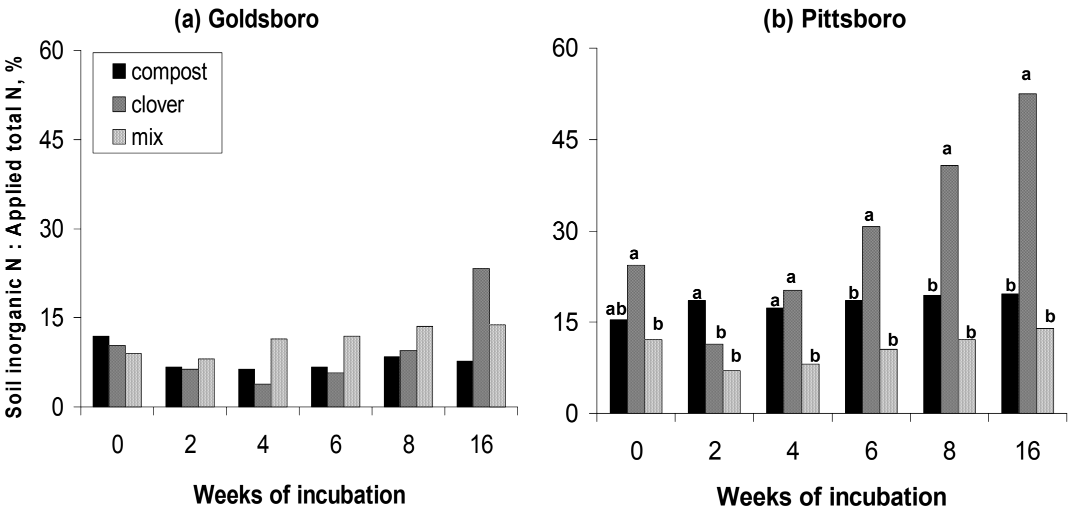

Figure 4.15: Proportion of available soil N to total N applied in compost, clover, and compost + clover (mix) amendments in (a) Goldsboro and (b) Pittsboro soil incubations. Bars with different letters indicate a significant difference at ($p<0.05$).

In the Pittsboro incubation, however, the proportion of SIN in the compost treatment was significantly greater ($P<0.01$) at Week 2 than the other two amended treatments, possibly due to the low C:N and small particle size of compost. The proportion of SIN in clover treatments decreased steeply at Week 2 as N was likely immobilized during initial decomposition. Over the following six weeks, however, clover treatments rose four-fold as more SIN became available ($p<0.05$). Mix treatments remained relatively stable over the course of the incubation, perhaps due to immobilization of clover N by the microorganisms assimilating substrates from compost. Duffera *et al*. (1999) reported 24 to 35% of N added as pelletized process swine lagoon solids was available in three North Carolina Coastal Plain Ultisols and one Inceptisol after sixteen weeks of incubation. In contrast, the authors concluded that only 10% of applied organic N was mineralized during the same period. Compost used in our experiment had high levels of organic N, resulting in a similar low proportion of available N during incubation.

4.4. Conclusion

The findings of this research have interesting implications for farmers in the Southeast. The synergistic effect observed in the lab incubation of the Goldsboro sandy loam may be useful to organic farmers in the Coastal Plain seeking to reduce inputs such as manure, poultry litter, and composted manure, which can contain high levels of phosphorus and metals.

Field experiments differed greatly from lab incubations due to high variation in moisture, temperature, microflora, leaching, and nutrient uptake by plants. Nevertheless, lab incubations can provide important insight into the dynamics of incorporated organic amendments in particular soils (Gale *et al*., 2002; Sanchez *et al*, 2001). Precipitation was up to four-fold higher than average during the field experiment and may have led to considerable leaching and more intense wetting and drying cycles not experienced in the lab incubation, resulting in differences in N mineralization. Additionally, compost and clover amendments were ground to 2 mm prior to addition to the incubation. These different particle sizes likely affected rates of mineralization compared to larger particle sizes resulting from field roto-tilling or disking of the crimson clover cover crop.

Difficulties in finding significance between treatments in the field experiment may largely be attributed to the inclusion of soymeal in the field experiment. While this addition served to equalize N levels across treatments, it may have masked treatment effects. Additionally, the low C:N ratio of the compost and high initial concentrations of available N may have led to quicker mineralization of N than would occur with a larger C:N ratio. Other studies have shown low N availability during the first season after compost application (Mamo *et al*., 1998; Eghball, 2000).

Further field trials are needed to determine the effect of particle size, soil texture, and climate on priming effect; when can it be expected to occur, and how much additional N this will provide. For Piedmont farmers on clay soils, combining compost and a cover crop may actually immobilize plant available N at a crucial period in a crop’s growth. Since sidedressing with compost is common practice among organic farmers in the Piedmont, further studies on timing of compost application to a field that has been cover cropped would help determine conditions when cover crop + compost would be beneficial to crop production. Similarly, since compost and cover crop synergy appears to be soil specific, researchers should continue to evaluate these interactions on a variety of soils in order that farmers in various cimatic or soil texture zones may better manage their organic amendments.

<u>Chapter 5</u>: Soil fertility management and compost use in Senegal's Peanut Basin

5.1. Soil fertility and food security in Senegal's Peanut Basin

As in most parts of semi-arid West Africa, the agricultural and ecological resources in Senegal are under increasing pressure from a growing population and intensive land use (Wezel and Rath, 2002). According to the Food and Agriculture Organization of the United Nations (FAO), in the four decades since Senegal's independence, cereal production has increased 68% to 886 Gg and area harvested has increased 25% to 1.2 million ha (FAOSTAT). Nevertheless, Senegal becomes more dependent on cereal imports as per capita production declines [Figure 5.1], a result of population growth coupled with declining yields due to low soil fertility and climatic variability. In order to meet basic production needs, farmers often increase the area under cultivation, curtailing or eliminating fallowing (Diop, 1999). Indeed, the total area of under permanent cropping has increased from 3,000 to 40,000 ha since 1961. Traditional fallow rotations of 10 to 30 years allowed for substantial nutrient accumulation via residue decomposition, manure, nitrogen (N) fixation by leguminous herbs and shrubs, and the recycling of deep-soil nutrients by grasses and trees (Esse *et al.*, 2001).

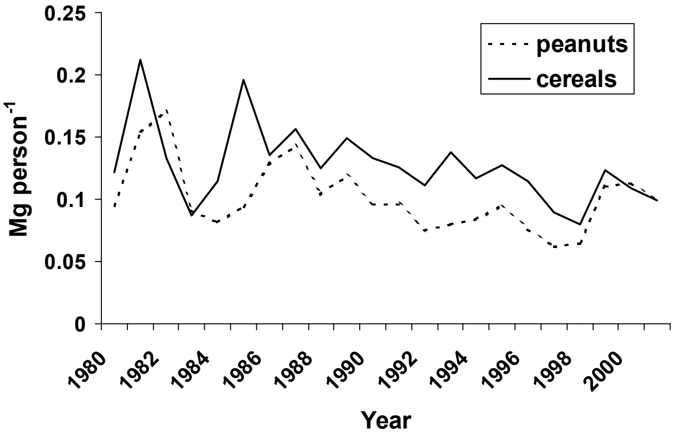

Figure 5.1: Per capita peanut and cereal production in Senegal, 1980-2001 (source data: FAOSTAT)

Nevertheless, current practices in the Sahel do not allow for an adequate regeneration of soil nutrient pools. Roose and Barthès (2001) calculated C losses of up 100 kg ha^{-1} year^{-1} in West Africa by erosion and leaching. As organic matter diminishes, the sandy soils are less able to retain nutrients and moisture (Diop, 1999). With the increase of cultivated area and the increasing scarcity of bush fallow, livestock grazing becomes more concentrated, leading to overgrazing and risk of desertification, as well as to a decline in livestock productivity (Wezel and Rath, 2002). To diversify income as crop prices fall, farmers may intensify small livestock production (Webb and Coppock, 1997). Increased grazing and deforestation have also been linked to reductions in soil faunal activity and water infiltration in Senegal (Sarr *et al*., 2001)

These issues are particularly acute in Senegal's Peanut Basin. Bordered by the littoral dunes to the West, silvopastoral savanna to the north and east, and The Gambia to the south, this agroecological zone has been the center of the nation's agricultural activity since the mid-19th century. Research has demonstrated a steady decline in soil carbon since 1850 due to clearing of trees and savanna, brush fires, and continuous cropping (Tschakert, 2001). Seventy to 80% of Peanut Basin soils are classified as *Jóór* (or in French, *Dior*), a sandy soil (Ustipsamment) with little ability to retain nutrients, due to low organic matter (0.3 to 1 %) and a mostly kaolinitic clay fraction. Fifteen to 25% of soils are the more fertile *Deg* (or *Deck*) soils (~Psammentic Haplustalf). Roughly half of arable land is cropped with millet (*Pennisetum glaucum*), 40% in peanuts (*Arachis hypogaea*), and 7% in cowpeas (*Vigna unguiculata*) (Institut Sénégalais de Recherches Agricoles, 1995; Rodale Institute, 1989).

The region of Thiès, in the heart of the Peanut Basin, is east of Senegal's capital Dakar and the second most populated region of Senegal, with 13.6% of the national population on 3.4% of the land (1.3 million people on 6,601 km^2) (Négri, 2001). Sixty-six percent of the population is rural, mostly working in agricultural production. The Thiès region produces 14% of the nation's peanuts, 12% of millet, 16% of cowpea, 10% of sweet potato (*Ipomoea batatas*), and 35% of cassava (*Manihot esculenta*). Due to its proximity to the densely populated Dakar region, Thiès produces the majority of vegetables in Senegal, averaging 40 to 60 Gg $year^{-1}$ between 1985 and 1995. The majority of this production is destined for consumption in Dakar, where the population is growing annually at 4%, much higher than the national rate of 2.9% (Mbaye, 1999).

The intensification of production on peri-urban (< 40 km from an urban center) and rural agricultural land within the Peanut Basin will certainly increase as urban populations continue to grow; urban dwellers in Senegal will outnumber rural inhabitants this decade

(FAOSTAT). Following urbanization trends elsewhere in the developing world, agricultural land is sold to developers, remaining fields are cultivated more intensively. Short tenure on land due to “squatting” generally leads to serious nutrient mining, so-called “hit-and-run” agriculture where famers crop intensively but apply few amendments to regenerate soil fertility (Dreschel *et al*., 1999). In an effort to offset declining yields and produce sufficient quantities of grain, farmers in nearby rural areas annually clear more land for cultivation. Fallow periods throughout the Peanut Basin have been shortened or eliminated altogether (Rodale Institute, 1989; Westley, 1997; Tschakert, 2001). Since yields are largely dependant on rainfall, drought years and a steady decline in annual precipitation over the last fifty years threaten rural food security considerably (Rodale Institute, 1989). In 2002, grain stocks in many villages of the Thiès region had been depleted by July, three months before the new harvest replenished them (Commisariat à la Sécurité Alimentaire, 2002).

5.2. Nutrient cycling in arid and semi-arid West Africa

In agro-pastoral farming systems, livestock rely on post-harvest cereal stover for forage. Ultimately, however, the removal of biomass through grain harvest or livestock grazing may lead to a nutrient imbalance. While most stover nutrients are recycled back to the soil in the form of manure, distribution is uneven. Variations in micro-topography and rainfall also lead to considerable leaching losses (Haque *et al*., 1995) and additional inputs are often necessary. Considerable research has focused on nutrient cycling in arid and semi-arid agroecological zones of West Africa. Several studies in the Sahel have reported nutrient imbalances on a field level following harvest or grazing, yet the sustainability of the entire village system has rarely been quantified. Krogh (1997) found that in Sahelian Burkina Faso, millet harvests of 100 to 500 kg ha^{-1} led to nutrient deficits of 3 to 23 kg nitrogen (N) ha^{-1} and 0.11 to 1.04 kg phosphorus (P) ha^{-1} in sandy fields, and 6 to 30 kg N ha^{-1} and 0.30 to 1.23 kg P ha^{-1} in loamy/clayey fields. On a village level, however, the average N and P balances were all positive, with the exception of a slight N deficit in the loamy/clayey soil. By evaluating nutrient balances on a community rather than field level, nutrients imported from the grazing of fallows and rangeland may balance uptake by crops. This “nutrient mining” of bush fallow is not sustainable, however, and minimal nutrient inputs are still required to ensure sustained productivity (Mueller *et al*., 2001). Manures, crop residues and mulches, leguminous cover crops, and composts are all sustainable means of providing adequate fertility to traditional agro-pastoral farming systems. Some argue that organic inputs are insufficient and suggest improving fallows with woody and herbaceous species (Badiane *et al*., 2001).

In urban and peri-urban agriculture, the nutrient deficit is greater than in rural areas. As urban populations grow, the flow of food into the city centers will increase. However, urban waste nutrients are generally lost to landfills and are rarely returned to zones of production (Leitzinger, 2001). Dreschel *et al*. (1999) note that while peri-urban farmers are aware of losses in soil fertility, they may not seek to ameliorate the situation due to land tenure constraints. Additionally, since many have migrated from rural areas, they may be unaware of urban waste amendments that can benefit crop production. As the population in peri-urban areas of the Peanut Basin continues to grow, soil fertility is likely to decline unless efforts are made to emphasize the importance of recycling organic matter into the soil.

5.2.1. Crop residues and mulching

A thick layer of organic residue can lead to improved yields by reducing erosion due to rain, decreasing the velocity of runoff, increasing soil water infiltration rate, increasing soil surface storage of rainwater, increasing porosity and structure, and promoting microbial activity. Increased mulch rates generally increase water availability, while infiltration rate is a function of the proportion of surface area mulched (Lal, 1990). Improvements in soil fertility due to mulching are generally associated with the addition of organic matter and increase of macrofaunal activity. Termites (Isoptera) facilitate the decomposition of the mulch layer and contribute to improved infiltration (Mando and Miedema, 1997; Mando and Brussard, 1999). Zaongo *et al*. (1997) reported that 12 Mg ha^{-1} crop residue mulch increased sorghum (*Sorghum bicolor*) growth by 17% and reduced evaporation by 28%. Moukam and Tchato (1987) used coffee (*Coffea* spp.) residue mulch on Cameroonian ferralitic soils and noted increased cation exchange and organic matter accumulation, in addition to increased exchangeable K and increased peanut and manioc yields. Wezel and Bocker (1999) used *Guiera senegalensis* branches to mulch pearl millet on a luvic Arenosol in Niger and noted that 1 Mg ha^{-1} mulch increased millet production between 68% and 94% above a no-mulch control over two years.

Various forms of mulching are traditionally practiced in West Africa, mostly in humid zones where there is more available vegetative biomass. In the more semi-arid regions, however, mulch availability is often limited by low biomass production and its value as fodder. Crop residue and grasses are often fed to animals or used as construction material. Farmers are therefore forced to prioritize and the immediate need for a grass mat or the cash earned by selling millet stover may outweigh the long-term benefit that mulching would provide (Wezel and Rath, 2002). The multi-purpose use of mulching materials is the greatest obstacle to expanding mulch use in semi-arid West Africa. Mossi farmers in northern Burkina Faso use a 2-cm (3 to 6 Mg ha^{-1}) layer of dry grass mulch (*Loudetia togoensis*) as an initial reclamation technique for marginal crusted land, but mulch supplies are rarely large enough to cover all of their fields. They prioritize mulch application in the following order: 1) amend a soil with low fertility, 2) prevent soil degradation, 3) retain soil humidity, and 4) protect soil from wind, rain, or heat. There is no interest in mulching fallow fields. Mulch use varies along ethnic lines; neighboring Fulani rarely use mulch on their crops (Slingerland and Masdewel, 1996). Scheidtweiler and Kromer (1996) note that the amount of crop residue needed for a 1 to 2 cm thick mulch is unavailable in most areas and living mulches provide competition for water and nutrients. In addition, Buerkert *et al*. (2000) claim that mulch-induced increases are negligible without additional P. Experiments were carried out in the Sudano-Sahelian, Sudanian, and Guinean agroecological zones, ranging in annual rainfall from 510 to 1300 mm. The authors reported that mulch effects strongly decreased from north to south away from the Sahel and that the effectiveness of mulch is often related to soil texture.

5.2.2. Manure

Many researchers have evaluated the benefits of manure on soil fertility and physical properties. Villenave *et al*. (2003) reported millet yield increases of 155% in field sub-plots amended with 20 Mg ha^{-1} near Nioro du Rip, Senegal. Soil inorganic N increased by 45%, while N flux increased by 150% and microbial biomass rose by 65%. Esse *et al*. (2001) reported the release of N, P, and potassium (K) from field-applied cattle (*Bos taurus*), sheep (*Ovis aries*), and goat (*Caprus hircus*) manure (18.8 Mg ha^{-1}) to be ten-fold higher than annual nutrient uptake by a millet crop in the Sahelian zone of Niger. Krogh (1997) estimated uptake of 10.7 kg N ha^{-1} and 0.9 kg P ha^{-1} by a 250 kg ha^{-1} millet yield on a sandy soil in Burkina Faso. Esse *et al*. (2001) concluded that annual manure applications of 2 to 3 Mg ha^{-1} four weeks after sowing rather than heavier, less frequent applications, would help reduce nutrient losses[1]. Brouwer and Powell (1998) calculated the nutrient balance in a pastoral cropping system in Niger and concluded that 2.5 Mg manure + urine ha^{-1} would be necessary to replenish nutrient uptake by a millet crop with a harvest index (grain:stover ratio) of 20%. Based on N and P uptake of a 500 kg ha^{-1} millet crop, Krogh (1997) calculated the manure need for up to 3.6 Mg ha^{-1} in a Sahelian farming system in Burkina Faso. In Niger, manure and urine applied to millet resulted in significantly higher yields, and N, P, and K uptake than those observed in plots amended solely with millet residues or dry manure (Ipke *et al*., 1999). The authors concluded that the high pH of the urine freed up aluminum-bound P in the kaolinitic clay fractions of the soil.

Powell *et al*. (1999) reported that manure alone provided sufficient N for a millet crop, and manure P was quickly mineralized and utilized by the crop, whereas crop residue and browse immobilized P. This is of particular interest due to the largely P-deficient nature of most arid semi-arid West African soils (Haque *et al*., 1995). The Rodale Institute worked in conjunction with the Institut Sénégalais de Recherche Agricole (ISRA) and local farmers in Ndiamsil, Senegal, to evaluate alternating years of manure (2 Mg ha^{-1} 2 years^{-1}) amended with rock phosphate (30 kg Taiba-37% P_2O_5 ha^{-1} 2 years^{-1}) on peanut and millet yields (Diop, 1999). Yields in fields treated with rock phosphate were 100% greater than unamended controls, 40% higher than manure applications without rock phosphate, and 55% greater than traditional applications of more or less manure than the experimental rate.

Haque *et al*. (1995) notes that farmers apply manure to 20 to 50% of their cultivated area annually, but the frequency depends on crop and stock densities and type of available animal manure. Additionally, in areas of higher rainfall, cropping is more intense and the predominance of cattle leads to greater manure availability. Contracts between herders and pastoralists are a common means of managing manure application, and result in manure applications five to thirteen times greater than in fields without such contracts (Wezel and Rath, 2002). In a survey of 192 farmers in four Niger villages, Williams (1999) found that

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[1] While this may be acceptable for cereal crops, application of manure to leafy or fruit-bearing crops might lead to increased risk of pathogen such as *E.coli* (Jones, 1999).

farmers who manured their fields owned more 129% more livestock a slightly greater portion (4%) of the land they farmed. Those who did not apply manure generally had 51% more land under cultivation and at a greater distance from their home (220%), had more land in fallow (171%), and had 18% more household labor available. Fifty-eight percent relied on manure hauled from animal pens around the village, 16% relied solely on household livestock corralled in their fields and 8% relied on contracts with pastoralists. The author also noted that the probability of manuring was significantly greater if a member of the household migrated elsewhere for work, sending home money and thereby increasing the likelihood of additional livestock purchases.

5.2.3. Compost

Compost in semi-arid West Africa consists of decomposed organic matter, generally manures, household waste and ashes, and crop residues. These same materials can be found in any household manure pile or trash heap, yet compost production requires different management. Production of a high quality, mature compost requires layering nitrogenous and carbonaceous materials, and ensuring adequate moisture and aeration. Improved aeration and moisture control increases microbial activity (Tiquia *et al*., 1996, 2002), thus speeding decomposition, limiting malodorous anaerobic activity, and reducing losses of nutrients to leaching and volatilization (Sánchez-Monedero *et al*, 2001; Shi *et al*., 1999). ”Pit composting” is a method that places organic wastes a in a below-ground depression or pit to reduce moisture loss. The pit is often lined with cement or cement blocks, often 2 to 3 m long, 1 to 1.5 m wide and 1 to 1.5 m deep. Composting in above ground piles is less labor intensive simply because it does not require the labor of pit construction. Extension work conducted by the Rodale Institute and ISRA has attracted the attention of many Senegalese farmers since the early 1990s (Diop, 1999), particularly women interested in vegetable production for supplemental income. Modest household compost application of 2 Mg ha^{-1} in the Bambey region resulted in millet yield increases of 243 kg ha^{-1}. Peanut increases of 45% over no compost controls were also reported. Researchers attribute these increases not only to nutrient availability, but also to improved soil physical properties over the five years of the study. During the same experiment, mean millet yield in plots amended with 2 and 4 Mg compost ha^{-1} was higher than in plots fertilized with the same rate of manure over a five-year period [Figure 5.2]. In Burkina Faso, Ouédraogo *et al*. (2001) reported increased sorghum yields on plots amended with 5 and 10 Mg ha^{-1} of compost, as well as increased cation exchange capacity (CEC). In a related survey, farmers from Burkina Faso identified low soil fertility and yield loss as their primary reason for adopting composting. Sixteen percent of those surveyed cited difficulties in obtaining chemical fertilizers, while 26% claimed to have been motivated by the success of others. Almost 80% of farmers surveyed assigned maize and sorghum crops highest priority for application. While only 10% cited vegetables as their first priority, the authors note that 98% of farmers who grew vegetables did use compost.

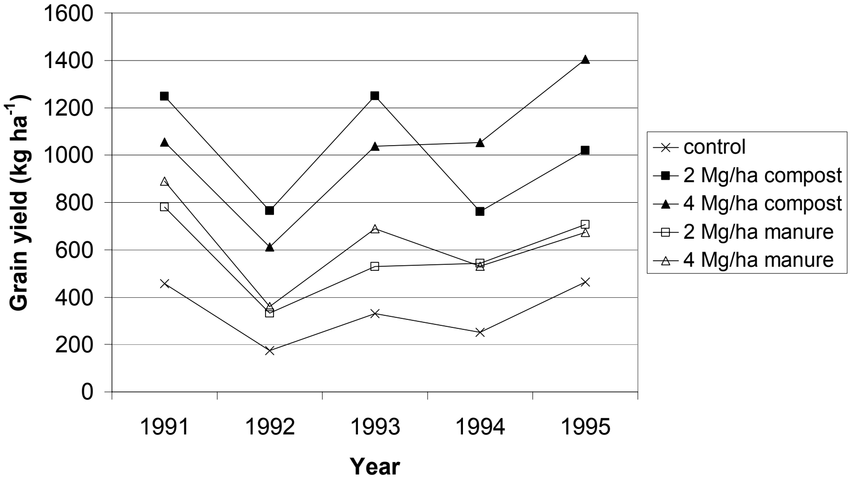

Figure 5.2: Millet grain yield in Ndiamsil, Senegal, 1991 to 1995 (source data: Westley, 1997)

The primary limitations to the adoption of compost cited is the labor required for production and application (Diop, 1999; Ouédraogo *et al*., 2001; Rodale Institute, 2002b), as well as the cost of equipment such as pickaxes, wheelbarrows, and carts. Several farmers in Burkina also identified land tenure as a constraint. Women and young farmers, in particular, may be less inclined to invest the energy into amending fields that they may not get to keep farming.

In an ongoing project serving five Peanut Basin villages in Senegal, the Rodale Institute promoted both pit and pile compost production among women's group members. In the second year of the project, women in the five villages produced over 8 Gg of compost. Nevertheless, the quantity produced was insufficient. Application rates of compost on millet, peanut, and cowpea fields ranged from 160 to 440 kg ha^{-1}, far below the 2 Mg ha^{-1}

recommended by Rodale [Table 5.1]. Manure application was higher, ranging from 1.1 to 1.5 Mg ha^{-1}, yet still lower than the 4 Mg ha^{-1} recommended rate. Participating women cited labor and manure shortages as the primary limitations to achieving recommended rates of amendment (Rodale Institute, 2002b).

Table 5.1: Application, plot size, and rate of compost and manure application in five Peanut Basin villages

	------------ Millet ------------			**------------ Peanut ------------**			**------------ Cowpea ------------**		
Material	**Amount applied** (Mg)	**Area amended** (ha)	**Mean Rate** (Mg ha^{-1})	**Amount applied** (Mg)	**Area amended** (ha)	**Mean rate** (Mg ha^{-1})	**Amount applied** (Mg)	**Area amended** (ha)	**Mean rate** (Mg ha^{-1})
Manure	15.86	13.86	1.14	13.52	11.74	1.15	5.75	5.43	1.05
Compost	0.98	4.26	0.23	0.41	2.56	0.16	0.61	1.38	0.44

(source data: Rodale Institute, 2002b)

5.3. Participatory research and local land classification and management

The need to involve local farmers in the development process has been increasingly recognized over the last few decades, and the use of baseline surveys to determine farmers' perceptions of soil fertility, soil conservation, and land use management has become prerequisite to research and development (Taylor-Powell *et al*., 1991; Doumbia *et al*., 1998; Baidu-Forson, 1999; Enyong *et al*., 1999). Traditional practices based on local knowledge are the result of a long process of evolution and testing, and are often well adapted to environmental and socioeconomic conditions. Because these are farmer-developed practices, farmers are more likely to adopt them quickly. While the technology may be adaptable to similar agroecosystems elsewhere, adoption is often localized and limited by a lack of infrastructure (Ouédraogo and Bertelsen, 1997). Nevertheless, traditional methods of soil fertility management have potential in maintaining productivity. Roose and Barthès (2001) contended: "Analyzing their limitations and improving these practices is probably much more efficient than introducing new technologies adapted to other climatic and socio-economic conditions."

By first understanding how farmers classify their land and prioritize nutrient management, we can better focus strategies to promote regenerative techniques. Kanté and Defoer (1996) surveyed Minianka farmers near Koutiala in the Sikasso Region of Mali, where 5-year mean rainfall has decreased over a few decades from 700 to 1,050 mm year^{-1} to 500 to 800 mm yr^{-1}. The purpose of their study was to understand the local land classification system, management strategies, and the resulting yields in an effort to guide future research and development activities. Using interviews and maps they were able to organize the Minianka classification of soils into five primary classes based on topography and the presence of coarse soil particles. Secondary classes were based on clay/sand content, color as an indicator of fertility, and suitability for crop production. Farmers used these classifications to determine land use strategy: crop selection, intensity, rotation, tillage, application of organic matter and fertilizer, and crop yield. They were aware of differences in each soil's susceptibility to erosion and understood that different erosion techniques are required for each. Similarly Ishida *et al*. (2001) surveyed Igbo farmers in eastern Nigeria to understand their soil classification system based on soil color, texture, and use. The Nupe of central Nigeria's system was based on clay content and water-holding capacity. Slingerland and Stork (2000) found that farmers in northern Burkina Faso used their local soil classification system to determine which soil and water conservation technology to use. Talawar and Rhoades (1998), however, in their extensive review of local soil classification studies, maintained that comparisons of local soil classifications to scientific taxonomy would be of more use when incorporated into a regional, macroscopic evaluation of local land-use:

> Local soil classification studies are—historically and ethnographically—typically based on "cognitive" approaches, while soil management research is focused on the records of day-to-day "practices" actually carried out by farmers. Even though the soil classification systems sometimes reflect the way soils are managed, understanding the classification alone does not necessarily explain or define actual use. A major challenge, therefore, is to link these two aspects—cognition and behavior—into a more meaningful ethnopedological framework.

This information is extremely valuable to the integration of sustainable management techniques into traditional farming systems and allows us to focus our research on systems relevant to the specific constraints identified by the local classification.

5.4. Methodology

Our study was completed over a three-month period from mid-August to mid-November 2003. Research objectives were to:

1. Characterize fertility management systems currently practiced by farmers working with the Rodale Institute in the Thiès and Diourbel regions of the Peanut Basin.
2. Characterize the manner in which composting technologies promoted by Rodale have been adapted to peri-urban and rural farming systems.
3. Determine the effect of compost use on crop performance and chemical soil quality indices.

During the three month period we made several visits to eight villages served by the Rodale Institute [Table 5.2], all within 55 km of Thiès (14º48’N 16º56’W). Qualitative information was collected from focus groups, informal and semi-structured interviews with individuals, and in-field visits. Almost all participants were members of the village GIE (*groupement d’interêt economique*, or village cooperative) and had participated in some Rodale extension activities. Questions focused on local land use classifications, perceptions of fertility, compost production and use, residue and manure management, and amendment rates and methods [Appendix]. Initially, early focus groups conducted at Keur Banda, Touba Peycouck, and Thiawène consisted of both men and women. After the first few groups, it became clear that women deferred to men’s authority and remained silent. Later focus groups were largely comprised of women with the exception of Touba Peycouck. Almost half of the individual interviews were conducted with male farmers.

Table 5.2: Peanut Basin villages included in qualitative survey, August to November 2003

Village	Département	Region	Distance from Thiès (km)	Focus groups held	Interviews conducted
Touba Peycouck	Thiès	Thiès	2	3	1
Keur Sa Daro	Notto	Thiès	12	0	1
Diouffène	Thiénéba	Thiès	25	2	1
Keur Banda	Thiénéba	Thiès	26	3	4
Taiba Ndao	Thiénéba	Thiès	28	1	2
Mboufta	Tivaouane	Thiès	45	0	1
Ndiamsil	Bambey	Diourbel	54	1	1
Thiawène	Bambey	Diourbel	55	3	4

From these villages, two villages representative of rural Peanut Basin farming systems (Thiawène and Keur Banda) were selected for soil analysis. Three farmers from each GIE were selected if they had used both compost and manure pile (*sëntaare*) material on the same crop in the same field on soil locally classed as *Jóór*. Sampling took place in Thiawène on 1 October 2003 from fields cropped with millet. Measurements were taken from four randomly placed 1m^2 quadrats in each area of amendment: compost, *sëntaare*, or none (12 quadrats total per farmer). Within each quadrat, four soil samples were collected with a stainless steel knife to a depth of 10 cm and composited in a plastic bucket. To assess crop performance, all millet plants within each quadrat were measured to obtain an average height per quadrat. Each farmer's compost and manure piles were also sampled two weeks later on 14 October 2003. In Keur Banda, compost and manure (*sëntaare*) piles were sampled on 30 September 2003, and fields sampled two weeks later on 13 October. Material from these piles had been used to amend fields in June 2003.

Because no Keur Banda farmers had used compost on their millet crops, the sampling protocol was modified for peanut fields. Additionally, because peanuts were not quite at harvest stage, farmers were hesitant to allow the destructive sampling of 12 m^2 of peanuts. As a compromise, three plants from each treatment were removed from each farmer's field. Peanut pods were removed and weighed. The remaining plant biomass (aboveground and coarse root mass) were shaken to remove excess dirt and weighed. Three peanut plants were weighed, sun-dried for two weeks, and weighed again to determine average moisture content. Soil samples were collected as in the other village. Mean precipitation in the Thiès region during the June through October 2003 rainy season was 348 mm (Direction Régionale du Développement Rural de Thiès, 2004).

All soil and waste samples were analyzed at North Carolina State University, Raleigh, NC. Waste samples were analyzed for total C, N, P, K, Ca, Mg, Na, Fe, and S by ICP-emission spectroscopy. Soil samples were sieved and ground to 2 mm. Available P, Ca, K, Na, Mg, and Al were determined by Mehlich-3 extraction (Mehlich, 1984). Total C was determined by combustion using a PerkinElmer 2400 CHN/O analyzer. Effective cation-exchange capacity (ECEC)—the available charge at soil pH—was derived from the sum, charge, and atomic weight of the cations. Nutrient concentrations were converted to kg ha^{-1} based on a depth of 10 cm and bulk density (Db) of 1.3 g cm^{-3}, the average Db of all fields at both sites. Excess soil was autoclaved to avoid escape of biological components. Data were analyzed using PROC GLM with LSD means comparisons (SAS Institute, Cary, NC). Peanut and millet data were tested for significance with within farm error, while soil data were tested with between farm error.

5.5. Results and Discussion

5.5.1. Local land use classification

Farmers interviewed in the focus groups classified their soils as *Deg* (~Psammentic Haplustalf) or the sandy *Jóór* (Ustipsamment) [Table 5.3]. As in the Minianka classification system discussed by Kanté and Defoer (1996), farmers first used texture and color to determine soil type. In almost every group, participants first described *Jóór* soils as being "soft." Similar to the Igbo classification system (Ishida *et al*., 2001), texture was followed by color: "white/light-colored," "reddish," or "yellow." *Deg* soils, on the other hand, were without fail described first by their dark color[2]. Following color, farmers described *Deg* soils as "hard." In one village, the word *xur* was used interchangeably with *Deg*. A *xur* is a low-lying area, a basin where *Deg* soils are generally found.

Table 5.3: Indicators of soil fertility used by farmers in eight Peanut Basin villages (Wolof terms in italics)

Fertility Indicators	**More fertile/productive**		**Less fertile/productive**	
	to have strength	*dafa am doole*	to have lost strength	*dafa nééw doole*
Soil type		*Deg/Deck**		*Jóór/Dior*
Color	black/dark	*ñuul*	white/light	*wééx*
			reddish	*xonq*
			yellowish	*soon*
Texture	soft	*nooy*	hard	*deger*
Crop performance	dark stalks/stover	*ñax dafa ñuul*	yellowish crops	*ñax dafa wééx*
	high yields		low yields	
Vegetation	grass/weeds	*ñax*	witchweed	*nduxum*
	Acacia albida	*kàdd*		

*with sufficient rainfall

While the concept of soil fertility is primarily based on productivity, farmers used the same indicators of soil type to describe fertility. A fertile or productive soil is considered "to have strength," and is first described as dark. A soil that has "lost strength" is recognized by its light color, and referred to with the same words used to describe a *Jóór*. Indeed, farmers view *Deg* soils as inherently more fertile due to their darker color and superior water-holding capacity. During interviews they generally qualified a statement such as "Deg soils are more

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[2] It should be noted that unlike color words borrowed from French (*soon* from *jaune* or *bulo* from *bleu*, for example), color words in Wolof are used relatively. *Ñuul* means "dark" more than "black", as it is often used to describe dark-skinned people. It is also the word used to describe the dark green color of healthy millet plants. Similarly *wééx* means anything very light-colored. *Xonq* means reddish, and is also used to describe the skin color of Arabs and Maures. The polyvalence of terms for these "colors" is also found in the soil descriptions of the nearby Manding (dark/black=*fin*, light/white=*jè*, and reddish=*bilen*).

fertile" with the caveat that rainfall must be sufficient. They usually added that during drought conditions, *Jóór* soils are more productive.

In addition to the preceding year's yield, plant health during the growing season itself serves as another indicator of soil fertility: dark green growth and the formation of thick heads. Abundant grass and broadleaf weed growth is another indicator of soil fertility, with the exception of parasitic witchweed (*Striga hermonthica*), whose presence is associated with poor fertility. Farmers recognized the fertilizing properties of leguminous *Acacia albida* trees, whose soil ameliorating properties have been extensively researched (Payne *et al.*, 1998; Weil and Mughogho, 1993).

5.5.2. Manure and compost use

Based on the above criteria, farmers apply manure, household waste, cooking ashes, and compost to their fields. Throughout the year, manure is collected from small livestock tethered or corraled in the family compound. Stabling of animals within the family compound increased rapidly throughout Senegal in the 1980s due to extension efforts by ISRA, which promoted the practice as a means of fattening livestock, increasing milk production, and reducing overgrazing (Fisher *et al.*, 2000). Manure primarily came from goats, sheep, and horses, since a contract herder outside the village generally tends cattle. When asked why cattle ownership was uncommon, farmers noted that cattle populations had declined due to disappearing fallows. This corresponds to FAO data showing stagnant cattle production [Figure 5.3], generally attributed to the droughts of the 1980s, as well as to diminished fallows (Westley, 1997).

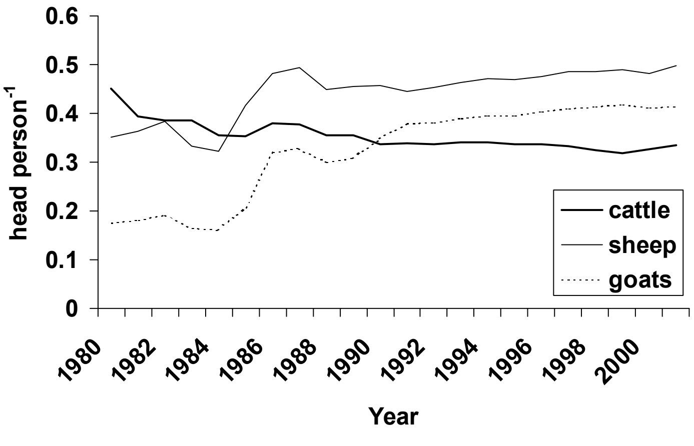

Figure 5.3: Per capita livestock production in Senegal, 1980-2001 (source data: FAOSTAT)

Manure is raked daily into a pile (*sëntaare*) in or next to the family compound [Figure 5.4]. Household waste, cooking ashes, and broken millet stalks are also added. Most farmers said they did not water or turn the pile. When field preparation begins in May or June, the pile is loaded onto a cart. Those who carted away *sëntaare* manure after two to four months noted that the piles were hot and smelled foul, suggesting anaerobic decomposition or ammonification of N (Elwell *et al*, 2001). Those who waited six to ten months claimed that pile did not smell and had become soil[3].

Figure 5.4: *Sëntaare* (manure and trash pile) in Thiawène in front of millet stalk fence (*sàkket*)

Figure 5.5: Keur Banda farmer with mature pile compost

All villages in our survey were selected because of their association with the Rodale Institute. Most of the focus group participants had attended composting trainings, and two villages, Mboufta and Ndiamsil, had been the site of extensive composting field trials in the early 1990s. At that time, labor-intensive pit composting was emphasized. As a result, composting had been almost entirely abandoned at the time of this survey. In the remaining villages studied, Rodale has emphasized less-labor intensive pile composting [Figure 5.5]. While pit composting is practiced in the women's group gardens as part of an ongoing project, many of the participants practiced pile composting at home as well. Pile composting in Thiawène, Keur Banda, and Touba Peycouck was widespread at the time of the survey. The feedstocks of both compost piles and *sëntaare* piles are essentially identical. Management of the two piles differs greatly, however. A *sëntaare* pile is left unattended, while a compost pile is turned and watered regularly. Additionally, carbonaceous and

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[3] The word *suuf* is used interchangeably for both soil and sand.

nitrogenous materials are layered when first making a compost pile to facilitate aeration and guarantee a relatively uniform blend.

Unlike the *sëntaare* pile, which is managed by the male head of household, compost production is usually managed by women[4]. When asked if the male head of household owns the compost, female respondents unanimously stated that he did not, but acknowledged that if he asks for it, they are obliged to comply. Farmers responded that s*ëntaare* piles, on the other hand, were the property of the male heads of household. Women said that their husbands rarely refused them access to the pile, but acknowledged that the husband's crops had priority over hers. Similarly, Westley (1997) reported that conflict over manure was rare but that some women joked about having to steal their husband's manure. Indeed, it may be that women only express discontent with the gender division of labor and control of resources through implicit forms of critique such as humor, since several women in our study commented that their primary responsibility was to their families. Similarly, Fisher *et al*. (2000) reported that while stabling of livestock required a 20% increase in labor for women in the Kolda region, 95% of those interviewed responded that the practice had improved their family welfare.

Because it is more labor intensive, compost production and use was much lower than manure use in the study villages. Those who made compost averaged two donkey cartloads (~1.5 m^3 each), while seven to twelve cartloads was the average amount of *sëntaare* manure used. The majority of organic material was applied to fields close to the household. Farmers prioritize application based on their crop selection. Fields where grain crops (millet and sorghum) are to be planted take priority. Peanuts and cowpeas generally follow cereals in rotation and are generally left unfertilized, relying solely on the residual fertilizing effect of the preceding year's manure. Some farmers noted the benefits of rotating cowpeas with grain. As a legume, cowpeas fix atmospheric N that the following crop can use. In the Ségou region of Mali, a Sahelo-Sudanian climate similar to Senegal's, Kouyaté and Juo (1998) rotated millet or sorghum with cowpea and reported that sorghum yields improved 48% over continuous cereal cropping by the third cycle of rotations. Based on the above land-use classifications and fertility criteria, farmers add manure or compost to fields or parts of fields they deem less fertile in an effort to equalize fertility across the field. Cartloads are dumped

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[4] Some male youth engaged in gardening also produce pile compost.

and spread manually with basins or shovels. A couple of participants stated that they amended half of the field one year, and the other half another year, often corresponding with crop rotation based on the suggestion of extension workers. More often, however, management is site-specific. If the field is mixed *Jóór* and *Deg* soils, the sandy *Jóór* receives the amendment. In most cases, however, the entire field is *Jóór*. Farmers then localize application, amending lighter areas, areas with high witchweed populations, or areas that yielded poorly in previous years. Site-specific management based on variations in the soil catena or previous poor crop performance suggests that local land use classifications and farmer knowledge adequately address the fertility constraints on micro-topographical, field, and landscape scales.

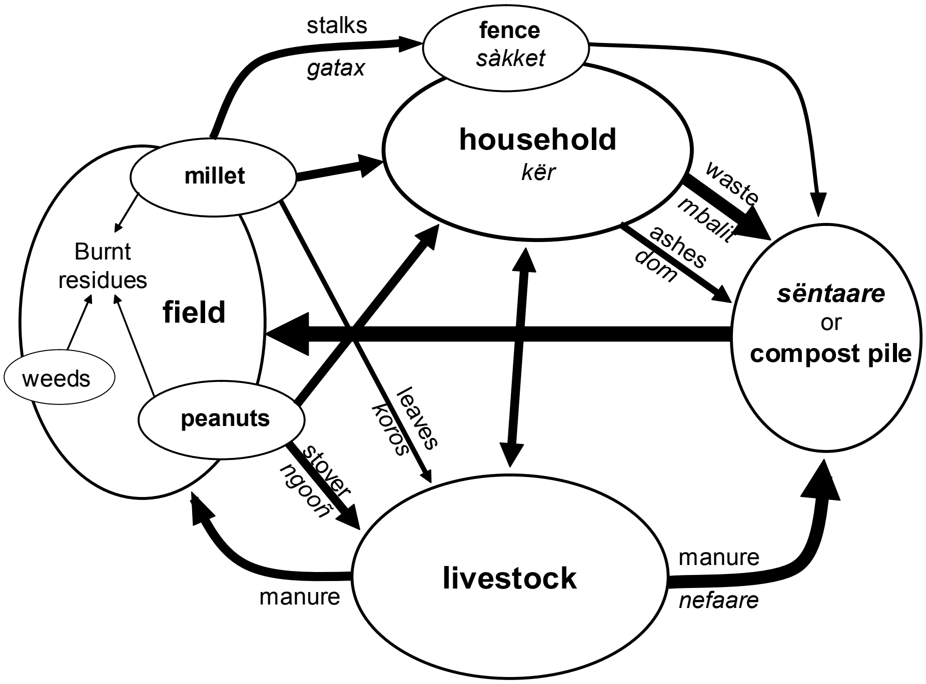

Figure 5.6: Schematic diagram of residue and waste cycling in surveyed Peanut Basin villages. Wolof terms appear in italics.

5.5.3. Residue management

Peanut stover is collected and saved as animal fodder to be used in the household during the dry season or sold. Following millet harvest, all green leaves are peeled from the stems and fed to livestock. One respondent explained, “We peel off the green leaves and feed them to our animals. They make manure for us that then goes back on the field.” Thick, sturdy stalks are selected and cut in the field for use as fencing around the family compound [Figure 5.4].

Broken or rotten fencing is added to *sëntaare* or compost piles. The stalks remaining in the field are broken at the surface, trampled, and grazed by livestock until field preparation the following year. The remaining undecomposed residue is removed at that time and piled along with all weeds and shrubs. Any edible or medicinal plants are gathered for use, and the piles of residue are burned in the field. The ash is not spread [Figure 5.6].

4.5.4. Compost and sëntaare pile chemical properties

Concentrations of C, N, P, K, Ca, Mg, Na, and Fe in compost pile and *sëntaare* pile samples were not significantly different between the two villages [Table 5.4]. Sulfur (S) concentrations in *sëntaare* pile samples in Keur Banda (0.9 g S kg^{-1}) were higher ($p<0.05$) than in Thiawène (0.5 g S kg^{-1}), however [data not presented]. This could be due to different levels of soil S and associated rates of S uptake by forage species. Additionally, Keur Banda is ~5 km south of the heavily trafficked Thiès-Diourbel highway, while Thiawène lies ~25 km north of this road. It is possible that atmospheric S originating from fossil fuel combustion could increase S concentrations in Keur Banda soil (Nyborg *et al*., 1991). Soil samples were not analyzed for total S.

Table 5.4: Mean chemical characteristics of compost and *sëntaare* manure at Keur Banda and Thiawène

		Total										
Treatment	**n**	**C**	**N**	**P**	**K**	**Ca**	**Mg**	**Na**	**S**	**Fe**	**pH**	**CN**
		g kg^{-1}										
Sëntaare	7	59.4	5.4	1.3	1.9	8.5	2.1	0.3	0.8	0.9	7.6	10.9
Compost	10	49.5	4.1	1.1	1.5	6.4	1.8	0.4	0.6	0.8	7.8	12.1
ANOVA	**df**											
Treatment	1	NS	NS	NS	NS	NS	NS	NS	NS	NS	*	*
Village	1	NS	NS	NS	NS	NS	NS	NS	*	NS	†	NS
Farmer (Village)	8	NS	NS	*	NS	NS	†	NS	NS	*	NS	NS
Treatment × Village	1	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
CV %		54	57	24	65	43	38	35	35	13	5	12

* *indicates significance at* $p<05$, *† at* $p<0.10$, NS *not significant* ($p>0.10$)

Analysis of variance revealed significant difference between farmers in levels of P and Fe and marginally significant difference in Mg. Differences may be attributed to varying rates and sources of manure used by each farmer during compost production. Each farmer added whatever type of manure was available to his or her pile. Carbonaceous content in some farmers' compost and *sëntaare* piles was visibly greater than in others. The coefficient of variance (CV) for C (54%), N (57%) and P (24%) between farmers was extremely high, suggesting a large variability in feedstocks. Some farmers surveyed had only a single goat, while others had several heads of different species. Because some manures conained greater P than others, and because some farmers simply added more manure to their *sëntaare* piles than others, nutrient concentration were variable. Additionally, compost maturity varied between farmers. Older, more mature compost may have experienced some leaching which could have led to lower nutrient concentrations.

Compost pH was significantly higher than *sëntaare* pile (manure) pH in both villages, supporting previous research findings that the composting process generally raises the pH of a substrate due to hydrogen lost as ammonia (NH_3) or water during the mineralization of ammonium (NH_4^+) to nitrate (NO_3^-) (Sánchez-Monedero *et al*, 2001). In Keur Banda, compost averaged pH 8.0 and *sëntaare* manure pH 7.8, while in Thiawène, *sëntaare* manure averaged pH 7.0 and compost pH 7.5. Differences in pH between the two villages were marginally significant. Again, feedstock variability may have led to greater levels in Keur Banda. Compost C:N was greater than *sëntaare* pile C:N. This can be attributed to lower total C levels associated with degradation of soluble C during the composting process, as well as leaching losses of N (Bernal *et al*., 1998a; Tiquia *et al*., 2002).

Analysis of material from compost and *sëntaare* piles in the two villages suggests little difference between the nutritive qualities of the two amendments. According to descriptions of compost preparation by Rodale Institute staff and publications (Diop, 1999; Rodale Institute, 1994) and by farmers interviewed in the eight villages, compost piles contain the same feedstocks as *sëntaare* piles: manure, household waste, ashes, and crop residues. Management of the piles differs considerably, however. Improved aeration via the initial layering of feedstocks and active turning and watering of a compost pile can lead to rapid decomposition of waste materials. In contrast, surveyed farmers responded that *sëntaare* piles generally remain static for several months. It is possible that composting may generally increase the rate of decomposition of waste materials, but that after several months, chemical indices may not significantly differ from the traditional management techniques described by farmers.

5.5.5. Millet at Thiawène

In the three Thiawène farms sampled, there was no significant difference in millet height between plants amended with compost or *sëntaare* manure [Figure 5.7]. As anticipated, mean millet height was significantly higher ($P<0.05$) in portions of fields amended with compost and *sëntaare* manure than in unamended portions. The compost-amended plants in one farmer's field (A. Mbaye) were taller and visibly greener [Figure 5.8], cited by several other farmers as "proof" that compost worked better than *sëntaare* manure. Upon visible inspection, stalks were thicker in compost-amended areas, and spindly in unamended areas [Figure 5.9]. There was no significant difference in millet height between farmers, regardless of different rates of *sëntaare* manure or compost application and variability in the nutritive quality of compost and *sëntaare* manure. Average plant densities in manure areas were significantly higher than controls, but the number of harvestable grain heads plant^{-1} and heads m^{-2} were not different ($p>0.05$) across treatments [Figure 5.7].

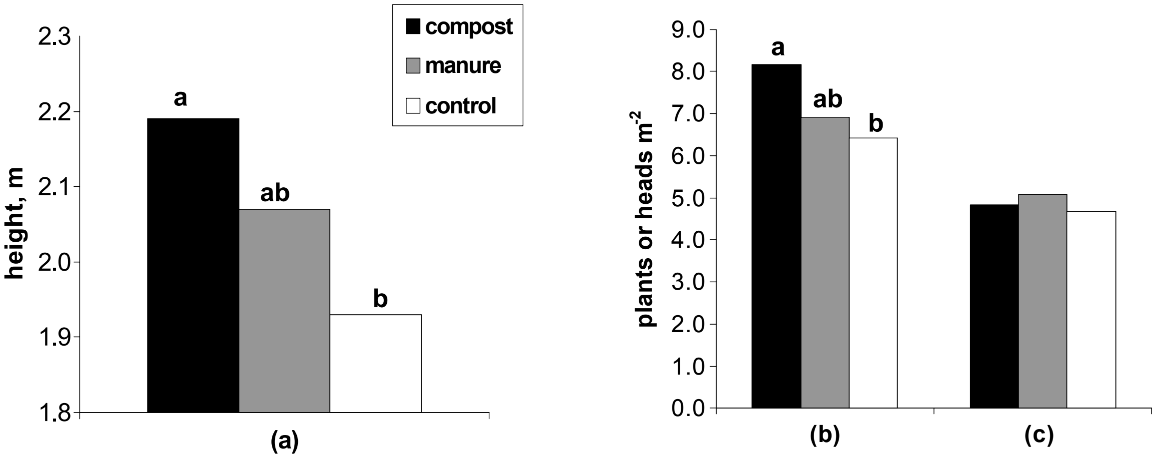

Figure 5.7: Effect of amendments on millet in Thiawène, 1 October 2003. (a) height (m), (b) plant density, and (c) head density. Bars with the same letter are not significantly different at $P<0.05$.

Figure 5.8: Farmer standing next to manure-amended millet (left) and compost-amended millet (right)

Figure 5.9: Unamended millet, Thiawène

While not statistically significant in this survey, the trend toward better crop performance in compost-amended areas was consistent with previous research in the Peanut Basin (Rodale Institute, 1990; Westley, 1997; Sène and Guéye, 1998; Diop, 1999). Higher C:N in compost compared to *sëntaare* piles may reduce the amount of N lost to volatilization (Ekinci *et al*., 2000). Low C:N in manure has been reported to lead to increased leaching losses of N when stockpiled and in the field (Brouwer and Powell, 1998; Petersen *et al*., 1998). Additionally, active thermophilic composting generally leads to an increase in plant-available N (PAN) concentrations (Sánchez-Monedero *et al*., 2001; Bernal *et al.*, 1998b), as well as humic matter and CEC (Vincelas-Akpa and Loquet, 1997; Bernal *et al*., 1998b; Tomati *et al*., 2000), thus limiting leaching potential of PAN and other nutrients.

5.5.6. Peanuts at Keur Banda

Average above- and below-ground plant biomass (DM) in the three farms surveyed was statistically the same in plants fertilized with *sëntaare* manure and compost treatments [Figure 5.10]. Peanuts grown on compost, however, yielded significantly greater biomass than those grown in unamended plots. Mean pod fresh weight in amended treatments was significantly greater than control [Figure 5.11]. Analysis of variance also revealed significant farmer and farmer × treatment effects, due to the large variability in pod weight between farmers. The significance of this variance is likely due to the fact that one farmer (S. Ndiaye) had planted his peanuts closely together, leading to stunted early season growth. Genotype differences in the local varieties used by farmers could account for additional variation. As with millet in Thiawène, the trend of improved growth performance in compost-amended peanuts was consistent with controlled experiments in the region (Westley, 1997; Diop, 1999).

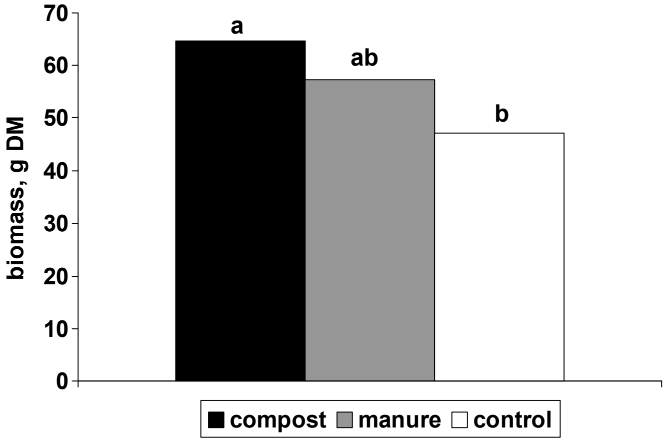

Figure 5.10: Effect of amendments on peanut biomass, Keur Banda, 13 October 2003. Bars with the same letter are not significantly different at P<0.05.

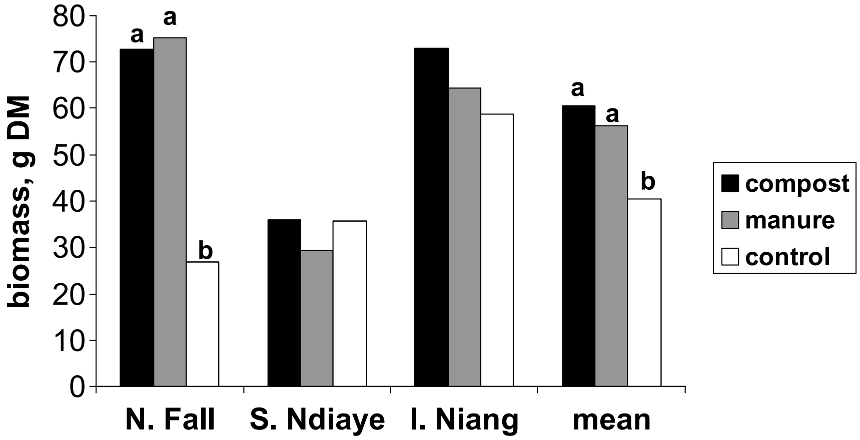

Figure 5.11: Farm-specific management effect on peanut pod weight, Keur Banda, 13 October 2003 Bars with the same letter are not significantly different at P<0.05.

Table 5.5: Chemical characteristics of field soil amended with *sëntaare* manure or compost and unamended soil at Keur Banda (13 October 2003) and Thiawène (1 October 2003)

	Bulk Density	**Total C**	**P**	**K**	**Ca**	**Mg**	**Na**	**Al**	**ECEC**
			Available						
	g cm^{-3}	kg ha^{-1}							cmol kg^{-1}
					Keur Banda				
Sëntaare	1.35	4,969	44	127	510	107	100	188	4.79
Compost	1.33	5,966	60	123	602	123	97	200	5.32
None	1.31	2,628	26	105	347	64	77	191	3.81
					Thiawène				
Sëntaare	1.34	3,597	28	114	367	78	61	179	3.83
Compost	1.31	4,117	52	150	564	129	62	209	5.24
None	1.37	2,990	25	105	336	70	58	172	3.58
					Mean				
Sëntaare	1.35	4,283	36	120ab	439	92ab	81	183ab	4.31ab
Compost	1.32	5,041	56	136a	583	126a	79	205a	5.28a
None	1.34	2,809	26	105a	342	67b	68	181b	3.69b
LSD	NS	NS	NS	26.2	NS	47.2	NS	21.6	1.42
ANOVA Variable#									
Treatment	NS	NS	NS	†	NS	*	NS	†	†
Village	NS	NS	NS	NS	NS	NS	†	NS	NS
Farmer (Village)	NS	†	NS	†	NS	*	**	***	NS
Treatment × Village	NS	NS	NS	NS	NS	NS	NS	NS	NS
CV %	44	50	60	16	45	37	17	9	27

**** indicates significance at p<0.001, ** at p<0.01, * at p<0.05, † at p<0.10,* NS *not significant (p>0.10)*
#Village variable tested using Type III MS Error term for Farmer(Village). Means in the same column followed by different letters are significantly different at p<.0.05

5.5.7. Analysis of soils amended with compost and sëntaare manure

In our survey area, soil Db averaged 1.3 g cm^{-3} across treatments, similar to Ustipsamments reported by Oluwasemire *et al.*, 2002. Total soil C ranged from 2 to 4 g kg^{-1}, or 2.6 to 6.0 Mg C ha^{-1} assuming a bulk density of 1.3 g cm^{-3} and depth of 10 cm [Table 5.5]. Total N levels were generally too low too be detected by a CHN analyzer (< 0.4 g kg^{-1}). Total C concentrations were similar to but slightly higher than those observed by Westley (1997). In her analysis of Rodale's replicated experimental plots in Ndiamsil amended with 2 and 4 Mg compost or manure ha^{-1}, Westley reported total C levels ranged from 2.4 to 2.9 g kg^{-1}, assuming Db of 1.3 g cm^{-3}, ~ 3.1 to 3.8 Mg C ha^{-1} at 10 cm depth. In Ndiamsil, plots were sampled in June prior to amendment, almost one year following previous year's amendment, whereas we sampled farmers' fields in October, immediately prior to harvest. In contrast, Gueye *et al*. (1986), reported 15.7 g C kg^{-1} in a *Jóór* soil removed from the "surface horizon" of control plots at the ISRA research station in Bambey. No further information on date of sampling or cultivation history was available, however. We suggest that higher levels of total C in our survey than in Westley's were associated with manure and compost residue that was still visible on the soil surface at the time of sampling. Differences in total C between the two villages may also be related to differences in management between peanut and millet crops. Amended areas were not significantly higher in total C than unamended areas, and perhaps due to high variance between farmers.

According to analysis of variance across both villages using a general linear model, soil differences between the two villages did not significantly affect soil chemical characteristics, with the exception of Na, which differed slightly between villages. Differences between farmers significantly affected Al, Na, and Mg, and marginally affected K and total C. There was no significant treatment × village interaction.

Compost increased K in the soil solution by 30% while *sëntaare* manure increased available K by 14%. Mg increases were also significant and 38% greater in manure-amended soils, and 89% greater in compost-amended. Villenave *et al*. (2003) reported K and Mg increases of 70% with manure application of 20 Mg ha^{-1} in two villages near Nioro du Rip at the southern extent of the Peanut Basin.

Changes in Ca and Al concentrations were also marginally significant. A trend appeared in which compost and *sëntaare* manure-amended soil Ca levels were 28 to 70% greater than those found in unamended soil. Contrary to our expectations, however, Al levels in compost-amended areas were also higher than in unamended parts of the field. Generally, Ca generally binds with Al, lowering available Al levels and reducing the risk of Al toxicity (Mokolobate and Haynes, 2002). Additionally, reductions in Al in compost-amended soils are associated with the liming capabilities of organic matter. It is possible that soil Al was assimilated by previous crops that were subsequently fed to livestock or recycled. Aluminum may have become concentrated in compost and *sëntaare* piles with repeated additions of manure and/or crop residues, and eventually returned to the field, raising soil Al.

Overall, it is likely that farmers' compost or *sëntaare* manure application may have actually mitigated some differences in soil fertility, thereby confounding treatment effects. In other words, unamended portions of the field—our baseline or control—may have been inherently more fertile and thus received no compost or manure. By adding compost or manure, the farmers may have increased the soil fertility to a level relative to what they perceived as the most fertile. Indeed, this is the intended effect of site-specific management. If a farmer noticed that crops were stunted in a particular area of a field, he applied compost or manure in an attempt to improve fertility and raise yield in less fertile areas of the field.

Effective CEC of compost-amended soil was significantly greater than ECEC of unamended soil. Soils amended with organic matter-rich compost or manure tended to have higher ECEC, largely due to large Ca and Al fractions. The average sum of base cations in unamended soils (2.14 cmol kg^{-1}) is similar to that of a *Jóór* soil analyzed by Charreau in 1974 that averaged 2 cmol kg^{-1} (Rodale Institute, 1989). Ouédraogo *et al*. (2001) reported CEC increase from 4 to 6 cmol kg^{-1} following applications of 5 and 10 Mg compost ha^{-1} to a soil in Burkina Faso. Wong *et al*. (1998) concluded that application of an amendment such as compost, organic matter binds cations in the soil solution, freeing up exchange sites in the soil particle.

High coefficients of variance in the above data can be largely attributed to differences between fields, farmer rates of application, and physico-chemical differences in the composts and manures applied by each farmer. Westley (1997) reported that soils in neighboring Ndiamsil amended with compost or manure had higher ($p<0.005$) total C concentrations than unamended controls. Her data was collected in a controlled experiment on fifteen adjacent plots measuring 10 m × 10 m. On the other hand, our survey was conducted on diverse fields amended by farmers at varying rates. Indeed, without a large sample, one can expect high variance in all on-farm research. A larger sample of farms could have reduced variability, reveal differences with greater accuracy, and supported previous findings of organic amendment-mitigated increases of soil C. A sampling of six farms does not provide sufficient data to draw more significant conclusions or to extrapolate our conclusions to other *Jóór* soils in the Peanut Basin. Unfortunately, logistical, funding, and time constraints prevented us from expanding our study to additional villages. Additionally, only three people in each village had applied both compost and *sëntaare* manure to the same crop in the same field, thus limiting our survey pool. Because it requires more labor to produce, farmers often reserve compost for use on only parts of the field with the lowest fertility, or on garden crops. The majority of farmers interviewed who practice composting produce only a small amount annually which they apply sparingly to an area in which they have a particular vested interest. The vast majority of participants, however, rely solely on manure from the household *sëntaare* pile. It was therefore difficult to identify farmers to participate in a study with stringent guidelines established to reduce statistical bias and variation.

5.6. Conclusions and recommendations for future work

Data from controlled experiments in the Peanut Basin have revealed improvements in both yield and total soil C concentrations with applications of compost and manure (Rodale Institute, 1990; Westley, 1997; Sène and Guéye, 1998; Diop, 1999). Nevertheless, on-farm data often differs considerably from such results due to various social, economic, and environmental constraints. One of our objectives was to evaluate the effects of compost application on crops and soils in the Peanut Basin. While we found differences in total soil C and available nutrient concentrations between amendments to be insignificant, trends in our data support previous research. A broader survey of a greater number of farms in several villages may have resulted in significant differences between treatments. The application of both compost and waste from the traditional household piles resulted in improved millet and peanut growth and increased availability of some soil nutrients.

An additional objective of this survey was to better understand Peanut Basin farmers' perceptions of fertility and to provide a "snapshot" of their subsequent management practices. Were extension workers to appreciate that farmers' fertility management strategies are based more on selective amending of priority crops and equilibrating less fertile soil rather than on distributing limited amendments evenly, they might find it necessary to reevaluate the promotion of a particular technique. With modified expectations, they might work more effectively with farmers to creatively modify existing management practices.

Another objective was to characterize farmers' adaptation of composting technology to socio-economic and environmental constraints. The majority of focus group and interview participants shifted from pit to pile composting either during or following involvement by Rodale technicians. They cited labor as the major constraint limiting compost production. Indeed, labor also seems to be the primary limitation to *sëntaare* manure use. Often more than half of fields were left unamended, yet many *sëntaare* piles were unused in all of the villages we visited. Several women complained that they had no means of transporting compost or manure to their fields other than in a basin or by borrowing a cart, similar to claims made by farmers in Mali, Niger, and Burkina Faso (Ouédraogo *et al*., 2001; Enyong *et al*., 1999). Nevertheless, farmers in our study were all acutely aware of the benefits derived from compost and manure application, and eagerly maintained that compost produces better results than *sëntaare* manure. If farmers were to actively manage *sëntaare* piles by turning or watering them monthly, they could ultimately produce satisfactory compost using a less labor-intensive process than that proposed by extension workers.

In the future, project workers might consider focusing on improved *sëntaare* management as a sustainable alternative to composting following the withdrawal of project support. Additionally, finding ways to facilitate transport of manure or compost to the field—particularly for women—could be a primary concern for development projects. Indeed, analysts often contend that food security in semi-arid West Africa and elsewhere in the developing world is often more a function of access and distribution than production (Pretty, 2002; Altieri and Rosset, 1999; Matlon and Adesina, 1997). Similarly, maintaining soil fertility in the Peanut Basin appears to also be more dependent on access to transport and labor than on availability of organic inputs. Nevertheless, the trend towards increasing OM in the region's sandy soils is a promising testament not only to the extension activities by NGOs such as the Rodale Institute, but also to the perseverance and adaptability of Senegalese farmers to increasingly challenging socioeconomic and ecological instability.

Chapter 6: The Rodale Institute and composting in Senegal's Peanut Basin—A case study

6.1. Overview

Since its arrival in Senegal in the 1980s, the Rodale Institute has promoted its vision of regenerative agriculture (RA) as a means of improving rural livelihoods, or as their slogan succinctly states: "Healthy soils, healthy food, healthy people." Rodale trains individual farmers, farmers' cooperatives, women's groups, NGOs, and government extension workers, in regenerative farming techniques such as organic matter recycling, seed saving, agroforestry, intercropping, and natural pest control. This training is combined with economic capacity-building in the form of training in micro-credit and the establishment of revolving loan initiatives to finance cooperative market gardening and animal husbandry.

Basic composting techniques have been a significant part of Rodale's RA extension work. Training sessions are designed to raise awareness about the importance of replenishing soil organic matter in the weathered, nutrient-poor, sandy soils of Senegal's Peanut Basin. Funded with the participation of various donor agencies over the last fifteen years, Rodale has trained thousands of farmers and extension workers in compost production using manure, crop residues, and household or municipal waste. Projects have ranged from promoting and experimenting with compost use on field crops such as millet, peanut, and cowpea in rural villages, to municipal waste management projects in Thiès and other cities.

For many years, Rodale has promoted the construction of compost pits as a means of optimizing compost production. Nevertheless, construction and maintenance of these pits is labor intensive, and farmers often abandon them after project completion. In a move to adapt to the socio-economic and environmental constraints preventing sustained compost use, Rodale has begun to promote pile composting in its partner villages, and has thus far received a favorable response from participants. By adapting compost production to local farming systems, or by simply improving upon existing practices, Rodale and other organizations devoted to sustainable agricultural development will ultimately see more widespread and continued practice among the farmers they serve.

6.2. Declining soil fertility in the Peanut Basin—Nature and scope of the problem

The Peanut Basin is a low-lying area roughly located between the Ferlo and Gambia rivers, bordered to the West by the littoral dunes (*niayes*) and the sylvopastoral scrub savanna to the East. Much of the native vegetation (*Adansonia* spp., *Barassus aethiopium*, *Acacia* spp.) was cleared with the intensification of agricultural production over the last 150 years. Peanut production expanded from the coast inland from the 1850s onwards and followed the expansion of the rail line eastwards in the early 20th century. Exports from this zone, largely controlled by colonial corporations such as the Compagnie Française de l'Afrique Occidentale, were Senegal's largest source of revenue, and by the 1920s, ~65,000 people migrated to the Peanut Basin each rainy season to work. Peanut exports peaked in the first few years of independence until world prices and drought resulted in a drop in production (Mackintosh, 1989).

The Peanut Basin remains Senegal's primary zone of agricultural activity. As a result, soil fertility has steadily declined due to cropping intensity and expansion into fallows. Research has demonstrated a steady decline in soil carbon since 1850 due to clearing of trees and savanna grasses and shrubs, continuous cropping, and brush fires (Tschakert, 2001). Seventy to 80% of the soils are locally known as *Jóór* (Dior), a sandy soil with little ability to retain nutrients due to low organic matter (3 to 10 g kg^{-1}) and mostly kaolinitic clay fraction. These soils are generally viewed by farmers as the least fertile and are cropped with peanuts (*Arachis hypogaea*) and pearl (souna) millet (*Pennisetum glaucum*). Fifteen to 25% of soils in the Peanut Basin are the more fertile and humic *Deg* (Deck) soils, used for millet, sorghum (*Sorghum bicolor*), and to a lesser extent, maize (*Zea mays*). Rich humic floodland soils[1] comprise only 2% of the land and are generally used for gardening (Rodale Institute, 1989). Approximately half of the area under cultivation is cropped with millet, 40% in peanuts, and 7% in cowpeas (*Vigna unguiculata*) (ISRA, 1995).

The Thiès region, east of Senegal's capital Dakar, is the second most populated zone of Senegal, averaging 178 inhabitants km^{-2}, or 13.6% of the national population on 3.35% of the land (1.3 million people on 6,601 km^2) (Négri, 2001). Sixty-six percent of the regional population is rural, mostly working in agricultural production. The region produces 14% of

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[1] According to USDA soil taxonomy, *Jóór* soils are Ustipsamments, *Deg* soils are Psammentic Haplustalfs, and the floodland soils Histisols or Vertisols.

national peanut production, 12% of millet, 16% of cowpea, 10% of sweet potato (*Ipomoea batatas*), and 35% of cassava (*Manihot esculenta*). Due to its proximity to the densely populated Dakar region, Thiès produces the majority of vegetables in Senegal, averaging 50 Gg year^{-1} between 1985 and 1995. Much of this production is destined for consumption in Dakar, where a population density of 10,500 people km^{-2} is growing at a rate of 4%, much higher than the national rate of 2.9% (Mbaye, 1999).

The swelling population of Dakar and the Cap Vert peninsula continues to have a pronounced effect on agriculture in the Thiès region. Consistent with urbanization trends throughout the developing world, rising land prices in peri-urban areas have resulted in the sale of agricultural land to developers. Remaining fields are farmed more intensively as urban expansion hems them in. Similarly, in nearby rural areas, population growth has led to intensification of farming and a decline in soil fertility. In an effort to offset the resulting decline in yield and produce sufficient quantities of grain, farmers clear more land for cultivation every year. Fallow periods throughout the Peanut Basin has been shortened or eliminated altogether. Yields are largely a function of rainfall due to the soil's poor ability to retain nutrients and the high-cost of chemical fertilizer (Rodale Institute, 1989). As a result, drought years seriously threaten rural food security. In 2002, grain stocks in many villages of the Thiès region had been depleted by July, three months before the new harvest replenished them (Commisariat à la Sécurité Alimentaire, 2002).

6.3. The Rodale Institute and regenerative agriculture

The Rodale Institute, based in Kutztown, Pennsylvania, and long-time advocates of organic, sustainable, and regenerative agriculture, began working in Senegal in the early 1980s. In 1987 following a "Senegalization" of management and staff, Rodale's *Centre Ressource pour une Agriculture Régénératrice* (CRAR) opened in Thiès. After a brief move to Dakar, and some name changes, Rodale returned to Thiès in early 2003 to be closer to the rural communities it serves. In its newest incarnation, the Senegal office continues to work with West African farmers as part of The New Farm initiative—the creation of a worldwide regenerative agriculture network linked by on-farm research, farmer-to-farmer exchange, and a website (www.newfarm.org).

In the ten years following the opening of the CRAR, Rodale trained over ten thousand farmers and technicians in regenerative agriculture (RA) techniques appropriate to the ecological constraints of the Sahel—composting, fodder cropping, agroforestry, intercropping, erosion control, livestock integration and husbandry, improved cookstoves, vegetable gardening, and tree nursery development. Additionally, training in microcredit management has been an integral part of community development and capacity-building projects. It is important to note that composting is only a single element of Rodale's overall mission to ensure sustainable livelihoods for Senegalese farmers. An appropriate technology "stepping stone," composting aids in the enhancement of soil fertility though organic matter cycling. For the purpose of this case study, however, Rodale's composting work provides an informative perspective on the potential successes and constraints facing development work.

6.4. Compost training and utilization in rural villages of the Peanut Basin

Compost production and use is central to the Rodale model of recycling organic matter to the soil. Between 1995 and 1997 alone, Rodale staff trained 869 people in composting techniques (Rodale Institute, 1997). Trainings are conducted with the expectation that the participants themselves will then perpetuate the technology on their own as the benefits of compost use become apparent. For example, following Rodale's work with the *Projet de Gestion des Eaux de Casamance* (PROGES), farmers set up 800 additional composting pits based on the ten constructed for training demonstrations. Simple, illustrated composting brochures in French and Wolof, Senegal's national language, have been distributed at many training sessions. Currently staff are creating training modules in French and Wolof for the New Farm website to be used by extension workers across West Africa.

Results from Rodale's on-farm compost experimentation have yielded productive results. In on-farm trials at N'Gombel and Mboufta, north of Thiès, millet grain yields (1.3 Mg ha^{-1} in plots fertilized with compost were 452% higher than unfertilized controls (230 kg ha^{-1}) [Table 6.1]. Increases in peanut yields were not as pronounced. Plots fertilized with compost yielded 2.4 Mg ha^{-1} of peanut biomass, 87% higher than controls, while those fertilized with manure only yielded 1.4 Mg ha^{-1}, representing only a 12% increase. Grain yields in manure plots were 610 kg ha^{-1}, or 39% above controls (440 kg ha^{-1}), and compost plots 91% higher than control (840 kg ha^{-1}). Farmers also reported the residual effect of compost application.

Table 6.1: Millet harvest at M'boufta, 1989, under different rates of compost application

Treatment	**Harvest count heads ha^{-1}**	**Head + grain yield kg ha^{-1}**	**Grain yield kg ha^{-1}**
Control	16,400	250	180
2 Mg compost ha^{-1} 2 $years^{-1}$	32,500	1,030	640
2 Mg compost ha^{-1} annual application	44,800	1,480	540
Local practice (more or less than 2 Mg compost ha^{-1})	25,000	850	520

source: Rodale Institute, 1990

In 1989, Rodale began work in conjunction with the national agricultural research institute in Bambey, the *Institut Sénégalais de la Recherche Agricole* (ISRA), on a composting project financed by USAID Natural Resource and Basic Agricultural Research (NRBAR) funds. Field trials were conducted in nearby Ndiamsil (Arrondissement of Baba Garage) from 1990 to 1995, the results of which have been heralded worldwide as testimony to the possibility of regenerative agriculture and organic matter recycling. Amendment rates of 2 and 4 Mg of compost led to considerably higher yields of millet grain than did manure at the same rates [Figure 6.1].

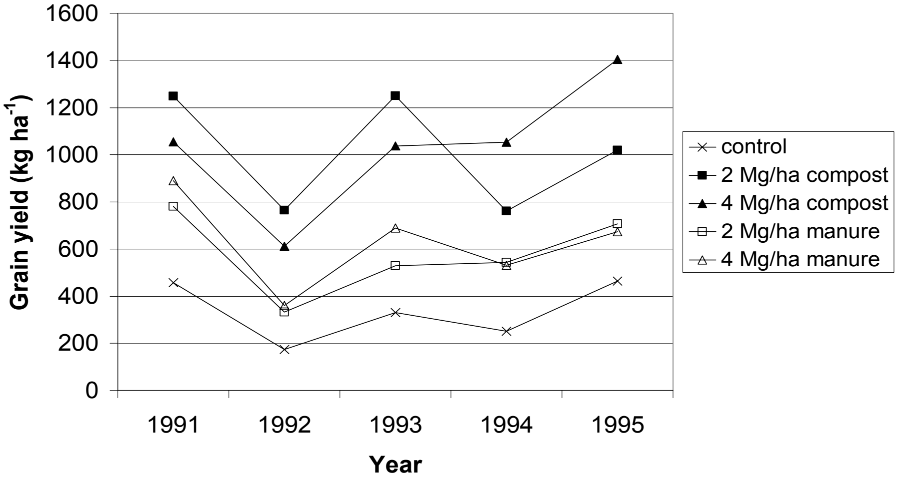

Figure 6.1: Millet grain yield in Ndiamsil, 1991 to 1995, under different rates of compost and manure (source data: Westley, 1997)

Millet straw and peanut seed yields followed a similar trend. The cumulative effect of the higher rate of compost (4 Mg ha^{-1}) was evident the fourth and fifth years of the experiment. An analysis of soil samples taken from test plots found that total carbon concentration in the top 10 cm of amended plots was significantly greater than in control plots (Westley, 1997), indicating the success of Rodale's efforts to increase soil organic matter.

In 1994, Rodale partnered with the USAID-funded PAONG (*Projet d'appui des ONGs*) to embark on a three-year project (1996-1999) in the Senegal River zone and the rainfed agriculture zone in the south. The funding, 136 million F CFA (~US$ 272,000 ca. 1996), was divided between the *Association Communautaire pour le Développement de Koumpentoum* (ACDK) based in Tambacounda, and the *Union des GIE du Delta* (UGIED) based in Saint-Louis. While the northern project was concerned primarily with promoting sustainable erosion control methods, the southern project's primary focused on regenerative agriculture—composting, agroforestry, and natural pest control. To demonstrate the residual benefits of compost, field trials were conducted in which millet was amended either with chemical fertilizer or compost. The second year, neither plot was amended. Yields on compost plots were double those of chemical plots, and plants showed better foliar development, thicker stalks, and longer heads with more grains (Sarr and Diallo, 2003).

From 1996 to 1998, Rodale collaborated with ISRA and the local population during a three-year program funded by USAID/NRBAR in several villages in the Région de Fatick, in the Sine River basin. The target area was the Serrer village Ndoff, population 273, with an average rainfall of 500 mm per year. The "training-of-trainers" program provided training in regenerative agriculture techniques to 139 people, 34 of them women, who then trained a total of 413 people in the surrounding communities. Twenty compost pits had been constructed by April 1997 at a cost of 272,500 F CFA (~$500) for materials (wheelbarrows, shovels, watering cans, pitchforks), one in each of the ten pilot villages and at the home of each *paysan animateur,* the villager charged with conducting post-training extension work. These villagers also facilitated on-farm trials, and were responsible for plot layout, data collection, and organizing meetings.

Farmers compared local varieties of millet and sorghum to improved cultivars on five different fertilization treatments: compost, manure, compost mixed with rock phosphate (RP), manure with RP, or local practices. Millet was planted at a density of 37,000 plants ha^{-1} by 11 different farmers, sorghum at a density of 93,700 by 6 farmers. Overall, yields were poor [Table 6.2] due to limited rainfall and a grasshopper infestation, but improved cultivars performed better under these conditions in all treatments except local millet under local practice which yielded 55% more grain than the hybrid. Amended compost and manure gave the best yields, followed by unamended compost, indicative of the paucity of available phosphorus in Peanut Basin soils (Sène and Guèye, 1998; Rodale Institute, 1998).

Table 6:2: Millet and sorghum yields at Ndoff, 1997, under different rates of compost and manure

Treatment	**Compost** (2 Mg ha^{-1}) + **RP** (30 kg ha^{-1})	**Compost** (2 Mg ha^{-1})	**Manure** (2 Mg ha^{-1}) + **RP** (30 kg ha^{-1})	**Manure** (2 Mg ha^{-1})	**Local practice** (< or > 2 Mg ha^{-1})
	kg ha^{-1}				
Local millet	420a	304b	333b	237b	314a
Souna 3 millet	522a	367a	398a	286a	202b
LSD	48.5	18.2	3.9	12	51
Local sorghum	1,037b	855b	687b	522b	412a
I45-66 sorghum	1,171a	1,003a	1,000a	699a	507a
LSD	30.7	19.6	79	68.7	96

Values in the same column followed by the same letter are not different ($P<0.05$).
Source data: Sène and Guéye, 1998

Currently, Rodale is working on a project funded by Vanderbilt Foundation entitled "Improving food production by using regenerative farming methods in five Senegalese villages." The project, now in its third and final year, has worked towards its objectives to promote regenerative agriculture techniques, increase cereal, fruit and vegetable yields, and reinforce capability of local people to manage organizations and finances. Four of the five villages are in the Thiès region: Keur Banda, Diouffene, Taiba Ndao, and Keur Sadaro. The village of Thiawène is located in the Région de Diourbel, adjacent to Ndiamsil where the Rodale Institute/ISRA composting trials were conducted. By July 2002, the end of the first year of the project, 141 people, 118 of them women, out of a total population of 643 had been trained in RA techniques. In November 2001, the first year of the project, four composting sessions were held, with 60 attendees (49 women). Six sacks of cement were given to each village for the construction of two 2 m^3 pits [Figure 6.2]. During the 2001-2002 gardening season, the villages produced 8.8 Gg of compost in the pits (Rodale Institute, 2002b). In July 2002 another composting session was held in each village, yet these sessions were poorly attended (36 women, 3 men) due to the heavy workload in the fields. In an effort to increase adoption of composting, Rodale emphasized pile composting during these sessions [Figure 6.3]. Compost piles, while slower to mature, require less maintenance than compost pits and are watered by rainfall. The 2002 sessions were mostly self-directed with occasional interaction by Rodale trainers.


Figure 6.2: Compost pits, Keur Sa Daro


Figure 6.3: Compost pile, Keur Banda

By the end of the first year, only 19 used compost (4%, up from 6% at the beginning of the project), while 73 of the project's participants used manure (52%, up from 43%) for their primary source of soil fertility (Rodale Institute, 2003). Rodale asked participants to use either compost at a rate of 2 metric tons per hectare, or manure at a rate of 4 Mg ha^{-1}. Participants grew millet, peanut, and cowpea in field trials, yet generally used less than the recommended rate [Table 6.3].

Table 6:3: Amount applied, plot size, and mean rate of compost and manure application in the five villages working with the Rodale Institute

	------------- **Millet** -------------			------------- **Peanut** --------------			------------- **Cowpea** -------------		
Material	Amount applied (Mg)	Area amended (ha)	Mean rate (Mg ha^{-1})	Amount applied (Mg)	Area amended (ha)	Mean Rate (Mg ha^{-1})	Amount applied (Mg)	Area amended (ha)	Mean rate (Mg ha^{-1})
Manure	15.86	13.86	1.14	13.52	11.74	1.15	5.75	5.43	1.05
Compost	0.98	4.26	0.23	0.41	2.56	0.16	0.61	1.38	0.44

Source data: Rodale Institute, 2002b

Factors limiting the use of manure were the large areas under cultivation and manure availability. Compost was used less often than manure because of the additional labor required. In the first year, 79% of millet fields were amended with manure, compared to 62% at the beginning of the project. Seventy-seven percent of peanut fields received manure, an increase of 7%. However, only half of cowpea fields were fertilized with manure, 10% less than before the project. Because manure availability is limited and because millet is a staple crop and peanuts are a cash crop, farmers prioritize fertilization. Additionally, cowpeas are generally cropped in rotation after millet or peanuts and benefit from the residual fertility value of the previous crop's heavier rate of amendment (Rodale Institute, 2002b).

6.5. Long-term impact of Rodale's composting activities

In 1997, Rodale conducted an impact survey to gauge the effectiveness and durability of its work in 73 villages in nine of Senegal's ten regions. Surveying a representative sub-sample of 17 villages, they used the following factors as indicators of their success: compost production, use of other RA techniques, understanding the RA philosophy, and ability to distinguish Rodale from other NGOs, and the continued transfer of RA techniques by participating farmers.

The villages were sorted into two groups to characterize trends of adoption. Group 1 villages—9 of the 17—were generally able to distinguish Rodale from other NGOs in the region and had a good understanding of regenerative agriculture, a relatively high rate of compost production (50%, range 40 to 90), mastered and used other RA technologies such as natural pest control and intercropping, and actively participated in the continued transfer of RA practices. These villages generally had access to credit, saw improvements to their production and increases in revenue, and had access to water (three of the villages had pumps).

Group 2, on the other hand, was unable to distinguish Rodale from other projects, and had a low rate of compost use (18%) and other RA technologies (25%). These villages generally had fewer material resources (such as tools needed for composting), fewer bovines and therefore less access to manure, less contact with other NGOs, and suffered from water constraints: low rainfall, low water table, salinity, and in a couple of the larger villages, high water costs. The impact survey also notes that activities in both groups dwindled or ceased altogether once Rodale withdrew (Rodale Institute, 1997).

An impact survey conducted in 2003 as follow-up for the PAONG project found that 75 % of the arrondissement of Koumpentoum (the villages of Koumpentoum, Kouthiaba, and Ida Mouride) practiced at least one of the techniques promoted by Rodale. Following the project, use of manure as an amendment was widespread, whereas before it was largely unused. The adoption rate of compost, however, was much lower, due primarily to the labor required to dig the pits, the limited availability and cost of cement, and insufficient quantities of manure to make large amounts of compost. Responding to these constraints, farmers in Darou Salam Thièkène switched over to pile composting, relying on the rain and occasionally watering. Previously they were able to harvest 2 Mg ha^{-1}, but declining soil fertility led to yields 68% less less than average. With the application of organic material, yields are slowly creeping back up to 1.5 Mg ha^{-1}. Overall there has been a drop in inorganic fertilizer use, largely due to rising costs, but also because farmers noticed an increase in parasitic witchweed (*Striga hermonthica*) infestation with chemical fertilizer (Sarr and Diallo, 2003).

From August to October 2003, a series of interviews and focus groups were conducted in the five Vanderbilt villages, as well as Ndiamsil, Touba Peycouck, and Mboufta. In Ndiamsil, compost use had largely been abandoned and farmers cited water as the primary constraint. Ndiamsil and twelve other villages rely on water from the well in neighboring Thiawène. Due to consistent shortages and disputes over access to the well, the women's garden was abandoned. The chief and his family continue to compost in pits, but most farmers fertilize their fields with decomposed material from the *sëntaare* (the household pile of manure, decomposed millet stalk from broken fences, cooking ashes, and food scraps). In all of the Vanderbilt villages, the majority of cropland was fertilized with manure from the *sëntaare*.

Like most technologies promoted by development workers, composting in the villages served by Rodale has evolved to meet the realities and constraints of local farming systems. In Touba Peycouck many women dug their own small pits in their family compound. These vary in size depending on the size of the family, but were neither cemented nor meet the dimensions specified by Rodale. In the Vanderbilt villages, Keur Banda and

Thiawène in particular, the majority of group members practiced pile composting in their compounds, while pit composting was only practiced in the pits constructed by Rodale in the communal gardens. While focus group participants recognized the superior benefits of compost on crop yield and plant health, they also noted that it is much more labor intensive. Average production was two to three cartloads, whereas the number of cartloads of *sëntaare* manure ranged from seven to twelve.

6.6. Lessons learned and recommendations for future work

The Rodale Institute's fifteen years of extension work in Senegal to promote regenerative agriculture have proven fruitful. In addition to enjoying widespread name recognition amongst rural farmers, Rodale has maintained its position as a central actor in the stewardship of Senegal's soils through the recycling of organic matter. The organizational emphasis on composting has been central to this mission.

Nevertheless, while on-farm experimental results have provided strong support for compost's potential as an organic amendment, the long-term adoption of composting by participating villages has been less successdul. In almost all cases where pit composting has been abandoned, farmers cited labor, cement, manure, and water as major constraints. Pit composting, while optimal in creating a quality product, is clearly not a sustainable solution. Rodale has taken note of this frustrating reality, as evidenced by the recent shift of emphasis to pile composting in the Vanderbilt villages. Yet even pile composting has its limitations. The minimal use of compost in the Vanderbilt villages is due to limited production. Again, labor is the primary constraint. *Sëntaare* manure remains the primary source of fertility in all of the Peanut Basin villages where Rodale presently works.

Integrating composting and *sëntaare* manure piles could therefore become an area of focus for Rodale's future activities. With minimal additional labor, a *sëntaare* pile can produce compost of the same quality, on a much larger scale. Interviews and focus groups revealed that manure piles are often anaerobic or actively composting (smelly or hot) when applied, but that older piles are indeed mature. By simply turning the manure pile monthly, farmers can reduce anaerobic activity and retain some of the nutrients lost to volatilization. On-farm experimenting with production methods—compost pile versus improved *sëntaare*, for example—could indeed elucidate the potential for quality compost production simply by modifying an existing local practice.

Rodale could also focus on the underscoring the importance of rock phosphate (RP) use. Focus group participants readily noted the purplish tint of millet leaves, a symptom of phosphorus deficiency. Yet none recognized the importance of RP distributed for free or at low-cost by the government. Most felt that it was simply useless clay powder, a waste residue from the national mines. The results of on-farm research, such as the NRBAR trials at Ndoff [Table 6.2], attest to RP's ability to improve crop yields in the nutrient-poor soils of the Peanut Basin. If sufficient quantities of RP were incorporated in the *sëntaare* piles, fields would receive a larger application of phosphorus than they currently receive. Additional demonstration plots using RP-amended *sëntaare* manure could be useful.

Rodale's strength lies in the diversity of its programs and approach. Its work with women's groups has been a successful means of empowering rural women in Senegal. Revolving-loan microcredit initiatives such as that of the Vanderbilt project are a proven means of increasing women's involvement in agriculture. The livestock fattening program (*embouche*) has provided women both with additional income and a source of manure. Because access to manure continues to constrain composting and organic matter cycling, compost and manure application are considerably below Rodale's recommended rates [Table 5.3]. By expanding the livestock program, Rodale can help to guarantee increased manure production and the return of organic matter to the fields.

Access to transport and labor also remain as factors limiting compost production, particularly for women. Many *sëntaare* piles remain unused for years due to labor constraints. Several women interviewed complained that they had no means to transport compost to their fields. They are dependent on their husbands or neighbors for use of a horse or donkey cart, and otherwise must carry the compost in large bowls or basins. This inefficient means of compost and manure application calls for improved access to equipment, either via individual purchase with revenues from the fattening program, or through communal ownership by the women's group or GIE.

In summary, Rodale could consider the following recommendations to improve adoption rates of composting by partner farmers:

1. Raise farmer awareness of phosphorus deficiency and the benefits of RP use. All future training workshops dealing with soil management could include phosphorus awareness, aided by demonstration plots. All future compost production could incorporate RP.

2. Evaluate the potential for improving traditional *sëntaare* manure piles by conducting a series of on-farm trials comparing pile compost production with traditional manure stocking practices and improved *sëntaare* management. Experiments could include laboratory analysis of both compost feedstock or substrate and finished product.

3. Raise farmer awareness (*sensibilisation*) of improved *sëntaare* management through a series of training workshops (*animations*) and incorporate the improved technology in future regenerative agriculture workshops.

4. Expand the livestock-fattening (*embouche*) program as a means of increasing manure production and revenue for women. The short-term economic gains from animal sales will continue to serve as an incentive for the integration of crop production and livestock.

5. Improve access to transportation equipment to facilitate compost and manure application in the fields.

Manure piles, or *sëntaare*s, remain a largely underutilized resource in the villages of the Peanut Basin. By integrating composting technology with this traditional practice of waste management—indeed, by simply *redefining* composting in the minds of farmers, by getting them to recognize that a manure pile can become a compost pile with a small amount of attention—the Rodale Institute can expect more widespread use of compost at rates sufficient to truly regenerate the soil.

Chapter 7: Conclusion

In the late 1970s, Masanobu Fukuouka mobilized a generation of organic farmers with his radical philosophy of "natural farming," a zero-tillage, zero-external input paradigm relying largely on the regenerative capacity of recycled crop residue mulch. He wrote:

> I believe that a revolution can begin from this one strand of straw. Seen at a glance, this rice straw may appear small and insignificant. Hardly anyone could believe that it could start a revolution. But I have come to realize the weight and power of this straw. For me, this revolution is very real. (Fukuouka, 1978)

The debate he sparked among practitioners of sustainable agriculture over the efficacy of such an approach to soil fertility management is ongoing. Nevertheless, the fundamental principle informing his "one-straw revolution" paradigm raises a fundamental point: the sustainability and integrity of agriculture and food systems depends on the recycling of organic matter (OM).

As this thesis has demonstrated, the production and utilization of compost and vermicompost is a potentially viable means of managing waste, improving soil physical properties, and cycling nutrients and OM back into agricultural soils, both in the modern production systems of the United States and in the subsistence systems on marginal lands of less industrialized countries. Nevertheless, a host of factors continue to compromise the widespread adoption of compost and vermicompost technology, including labor constraints, high variability of compost quality, and the potential loading of soils with phosphorus and trace metals.

Rather than promote compost worldwide as the next revolution in soil fertility and waste management, we must continue to identify how it can be integrated into particular farming systems, with careful consideration of site-specific social, economic, and ecological realities. By employing such a strategic approach, farmers, consumers, scientists, and extension workers may ultimately be more successful in their efforts to steward the land in an environmentally sound manner within the context of the post-Green Revolution challenges to worldwide food security discussed in Chapter 1. Jules Pretty writes:

> Strangely, most contemporary debates on human-nature interactions focus on how nature has been shaped by us, without fully accepting the second part of this equation: that we, too, must be shaped by this connection, by nature itself. We are also shaped by our systems of food production, as they, in turn, shape nature, and rely upon its

> resources for success—whether we approve or disapprove, whether the food system is local or distant. We are, of course, fundamentally shaped by the food itself. Without food, we are clearly nothing. […] once we understand the fundamental nature of this connection, then we start to see options for personal, collective, and global recovery. (Pretty, 2002)

His argument that sustainability is dependant on recognizing the interconnectedness of food, farms, land, and consumers is centuries-old, yet is especially poignant today as populations grow, economies consolidate, and resources are threatened. While continued research and development is needed to further evaluate the economic and agroecological potential of composting technology, its responsible integration into agriculture can continue to serve as one of many tools used to foster sustainable food systems worldwide.

Literature Cited

Aggelides, S.M., and P.A. Londra. 2000. Effects of compost produced from town wastes and sewage sludge on the physical properties of a loamy and a clay soil. *Bioresource Technology* 71:253-259.

Albanell, E., J. Plaixats, and T. Cabrero. 1988. Chemical changes during vermicomposting (*Eisenia fetida*) of sheep manure mixed with cotton industrial wastes. *Biology & Fertility of Soils* 6:266-269.

Aldrich, S.R., W.O. Scott, and E.R. Leng. 1975. *Modern Corn Production*, A & L Publications, Champaign, IL, 378 pp.

Alter, D., and A. Mitchell. 1992. Use of vermicompost as an aluminium inhibitor in aqueous solutions. *Communications in Soil Science & Plant Analysis* 23: 231-240.

Altieri, M. 1995. *Agroecology: The Science of Sustainable Agriculture*. Ch. 15: Plant Disease Ecology and Management, Westview Press, Boulder, CO, 307-320.

Altieri, M., and P. Rosset. 1999. Ten reasons why biotechnology will not ensure food security, protect the environment and reduce poverty in the developing world. *AgBioForum* 2:155-162.

Appelhof, M., K. Webster and J. Buckerfield. 1996. Vermicomposting in Australia and New Zealand. *BioCycle*, June, 63-64, 66.

Ascher, W., and R. Healy. 1990. *Natural Resource Policymaking in Developing Countries: Environment, Economic Growth, and Income Distribution*. Duke University Press, Durham, NC, 223 pp.

Ashraft, M., and H. Rehman. 1999. Mineral nutrient status of corn in relation to nitrate and long-term waterlogging. *Journal of Plant Nutrition* 22:1253-1268.

Ashok Kumar, C. 1994. *State of the art report on vermiculture in India*. Development Alternatives, Bangalore, 60 pp.

Astier, M., P.L. Gersper, and M. Buchanan. 1994. Combing legumes and compost: A viable alternative for farmers in conversion to organic agriculture. *Compost Science and Utilization* 2:80-87.

Aston, R.J. 1988. The case for temperature control in vermiculture. *In* C.A. Edwards and E.F. Neuhauser (eds). *Earthworms in Waste and Environmental Management*, SPB Academic Publishing, The Hague, 135-143.

Atiyeh, R.M., N. Arancon, C.A. Edwards, and J.D. Metzger. 2000a. Influence of earthworm-processed pig manure on the growth and yield of greenhouse tomatoes. *Bioresource Technology* 75:175-180.

Atiyeh, R.M., C.A. Edwards, S. Subler, J.D. Metzger. 2000b. Earthworm-processed organic wastes as components of horticultural potting media for growing marigold and vegetable seedlings. *Compost Science and Utilization* 8:215-223.

Atiyeh, R.M., C.A. Edwards, S. Subler, and J.D. Metzger. 2001. Pig manure vermicompost as a component of a horticultural bedding plant medium: effects on phyisiochemical properties and plant growth. *Bioresource Technology* 78:11-20.

Badiane, N.N.Y., J.L. Chotte, E. Pate, D. Masse, and C. Rouland. 2001. Use of soil enzyme activities to monitor soil quality in natural and improved fallows in tropical regions. *Applied Soil Ecology* 18:229-238.

Baidu-Forson, J. 1999. Factors influencing adoption of land-enhancing technology in the Sahel: lessons from a case study in Niger. *Agricultural Economics* 20:231-239.

Baker, R. 1968. Mechanisms of biological control of soil-borne pathogens. *In* J.G. Horsfall, K.F. Baker, and D.C. Hildebrand (eds.) *Annual Review of Phytopathology*. Annual reviews, Palo Alto, CA, 263-287.

Bamforth, S.S. 1999. Soil microfauna: Diversity and applications of protozoans in soil. *In* W.W. Collins and C.O. Qualset (eds.) *Biodiversity in Agroecoystems*, CRC Press, Boca Raton, FL, 19-47.

Bansal, S., and K.K Kapoor. 2000. Vermicomposting of crop residues and cattle dung with *Eisenia foetida*. *Bioresource Technology* 73:95-98.

Barbier, E.B. 1997. Macroeconomic and sectoral policies, natural resources, and sustainable agricultural growth. *In* S.A. Vosti and T. Reardon (eds.). *Sustainability, Growth, and Poverty Alleviation: A Policy and Agroecological Perspective*, Johns Hopkins University Press, Baltimore, 119-134.

Barrington. S., D. Choinière, M., Trigui, and W. Knight. 2002. Effects of carbon source on compost nitrogen and carbon losses. *Bioresource Technology* 83:189-194.

Beckwith, C.P., J. Cooper, K.A. Smith, and M.A. Shepherd. 1998. Nitrate leaching loss following application of organic manures to sandy soils in arable cropping. I. Effects of application time, manure type, over winter crop cover and nitrogen inhibition. *Soil Use & Management* 14:123-130.

Beetz, A. 1999. Worms for composting (vermicomposting). Livestock technical note. ATTRA, Fayetteville, AR.

Belete, L., W. Egger, C. Neunhauserer, H. Insam, and B. Caballero. 2001. Can community level physiological profiles be used for compost maturity testing? *Compost Science & Utilization* 9:13-18.

Bending, G.D., and M.K. Turner. 1999. Interaction of biochemical quality and particle size of crop residues and its effect on the microbial biomass and nitrogen dynamics following incorporation into soil. *Biology & Fertility of Soils* 29:319-327.

Benitez, E., C. Elvira, M. Gomez, F. Gallardo-Lara, and R. Nogales. 1996. Leachates from a vermicomposting process: a possible new liquid fertilizer? *In* C. Rodriguez-Barrueco (ed.) *Fertilizers and Environment*, Kluwer Acad Pub, Amsterdam, 323-326.

Bernal, M.P., M.A. Sánchez-Monedero, C. Paredes, and A. Roig. 1998a. Carbon mineralization from organic wastes at different composting stages during their incubation with soil. *Agriculture, Ecosystems & Environment* 69:175-189.

Bernal, M.P., C. Paredes, M.A. Sánchez-Monedero, J. Cegarra. 1998b. Maturity and stability parameters of composts with a wide range of organic wastes. *Bioresource Technology* 63:91-99.

Bittenbender, H.C., N.V. Hue, K. Fleming, and H. Brown. 1998. Sustainability of organic fertilization of macadamia with macadamia husk-manure compost. *Communications in Soil Science and Plant Analysis* 29:409-419.

Bouché, M.B. 1987. Emergence and development of vermiculture and vermicomposting: from a hobby to an industry, from marketing to biotechnology, from irrational to credible practices. *In* A.M. Bonvicini Pagliai and P. Omodeo (eds.) *On Earthworms*. Selected Symposia and Monographs U.Z.I., 2, Mucchi, Modena, 519-531.

Brady, N.C., and R.R. Weil. 2002. *The Nature and Property of Soils*, 13th Ed. Prentice Hall, Upper Saddle River, NJ, 960 pp.

Brewer, L.J., and D.M. Sullivan. 2002. Maturity and stability evaluation of composted yard trimmings. Proc Intl Composting and Compost Sci Symposium, Columbus, Ohio: CD Rom.

British Columbia Ministry of Agriculture, Food and Fisheries. 1996. Economics of Composting. Composting Factsheet. Online: http://www.agf.gov.bc.ca/resmgmt/publist/300series/382500-14.pdf

Brouwer, J., and J.M. Powell. 1998. Increasing nutrient use efficiency in West African agriculture: the impact of micro-topography on nutrient leaching from cattle and sheep manure. *Agriculture, Ecosystems & Environment* 71: 229-239.

Buchanan, M.A., G. Russel, and S.D. Block. 1988. Chemical characterization and nitrogen mineralization potentials of vermicomposts derived from differing organic wastes. *In* C.A. Edwards and E.F. Neuhauser (eds.) *Earthworms in waste and environmental management*. SPB Academic Publishing, The Hague, 231-239.

Buerkert, A., A. Bationo and K. Dossa. 2000. Mechanisms of residue mulch-induced cereal growth increases in West Africa. *Soil Science Society of America Journal* 64:346-358.

Bulluck, L.R. III, and J.B. Ristaino. 2002. Effect of synthetic and organic soil fertility amendments on southern blight, soil microbial communities, and yield of processing tomatoes. *Phytopathology* 92:181-189.

Bulluck, L.R. III, M. Brosius, G.K. Evanylo, J.B. Ristaino. 2002. Organic and synthetic fertility amendments influence soil microbial, physical and chemical properties on organic and conventional farms. *Applied Soil Ecology* 19: 147-160.

Cabrera, M.L. 1993. Modeling the flush of nitrogen mineralization caused by drying and rewetting soils. *Soil Science Society of America Journal* 57:63-66.

Caravaca, F., A. Lax, and J. Albaladejo. 2001. Soil aggregate stability and organic matter in clay and fine silt fractions in urban-refuse amended semiarid soils. *Soil Science Society of America Journal* 65:1235-1238.

Casalicchio, G., and P.L. Graziano. 1987. A comparison of compost and worm casting from solid municipal waste and sewage sludge. *In* A.M. Bonvicini and P. Omodeo (eds.) *On Earthworms*. Selected Symposia and Monographs U.Z.I., Modena, 437-457.

Chambers, J. 2002. Continuous flow for vermicomposting. *BioCycle*, February, 34-35.

Chen, C., R.R. Bélanger, N.Benhamou, and T.C. Paulitz. 2000. Defense enzymes induced in cucumber roots by treatment with plant growth-promoting rhizobacteria (PGPR) and *Pythium aphanidermatum*. *Physiological Molecular Plant Pathology* 56:13-23.

Chopra, K., and C.H.H. Rao. 1997. Institutional and Technological perspectives on the links between agricultural sustainability and poverty: Illustrations from India. *In* S.A. Vosti and T. Reardon (eds.).

Sustainability, Growth, and Poverty Alleviation: A Policy and Agroecological Perspective, Johns Hopkins University Press, Baltimore, 304-314.

Chowdappa, P., C.C. Biddappa and S. Sujatha. 1999. Efficient recycling of organic wastes in arecanut (*Areca catechu*) and cocoa (*Theobroma cacao*) plantation through vermicomposting. *Indian Journal of Agricultural Sciences* 69:563-566.

Commissariat à la Sécurité Alimentaire (CSA). 2002. Observatoire sur la Sécurité Alimentaire, July 2002. Bulletin No. 31, CSA, Dakar.

Conway, G. 1997. *The Doubly Green Revolution: Food for all in the 21st Century*, Cornell University Press, Ithaca, NY, 335 pp.

Conway, G., and E.B. Barbier. 1990. *After the Green Revolution: Sustainable Agriculture for Development*, Earthscan Publications, London, 205 pp.

Crozier, C.R., L.D. King, and G.D. Hoyt. 1994. Tracing nitrogen movement in corn production systems in the North Carolina Piedmont: analysis of nitrogen pool site. *Agronomy Journal* 86:642-649.

Damicone, J. 1996. Fungicide resistance management. Oklahoma Cooperative Extension Fact Sheet F-7663. Online: http://osuextra.com/pdfs/F-7663web.pdf

de Bertoldi, M., G. Vallini, A. Pera, and F. Zucconi. 1982. Comparison of three windrow compost systems. *BioCycle*, March/April, 45-50.

de Bertoldi, M., G. Vallini, and A. Pera. 1984. Technological aspects of composting including modeling an microbiology. *In* J.K.R. Gasser (ed.) *Composting of agricultural and other wastes*, Elsevier Applied Science Publishers, London, 27-41.

Debosz, K., S.O. Petersen, L.K. Kure, and P. Ambus. 2002. Evaluating effects of sewage sludge and household compost on soil physical, chemical and microbiological properties. *Applied Soil Ecology* 19:237-248.

Decker, A.M., A.J. Clark, J.J. Meisinger, F.R. Mulford, and M.S. McIntosh. 1994. Legume cover crop contributions to no-tillage corn production. *Agronomy Journal* 86:126-135.

DeLuca, T.H., and D.K. DeLuca. 1997. Composting for feedlot manure management and soil quality. *Journal of Production Agriculture* 10:236-241.

Dembélé, E. 1998. Expérience de la Compagnie malienne de développement des textiles dans la réalisation des soles fourragères plurannuelles. In *Plantes de couverture en Afrique de l'ouest*, International Development Research Centre (IDRC/CRDI), Online: www.idrc.ca

Diop, A.M. 1999. Sustainable agriculture: New paradigms and old practices? Increased production with management of organic inputs in Senegal. *Environment, Development & Sustainability* 1:285-296.

Direction Régionale du Développement Rural de Thiès. 2004. Pluviometrie Campagne Agricole 2003/2004, Fiche Recapitulative, Thiès.

Dominguez, J., and C.A. Edwards. 1997. Effects of stocking rate and moisture content on the growth and maturation of *Eisenia andrei* (oligochaeta) in pig manure. *Soil Biology & Biochemistry* 29:743-746.

Doumbia, M., A. Coulibaly, O. Coulibaly, Z. Kouyaté, A. Sidibé, F. Smith, L. Hossner, and J. Smyth. 1998. Baseline study of socio-economic conditions and decision making processes with a focus on small-farmers, nutrient management and millet production in the Ségou region of Mali. USAID, SM-CRSP IntDSS Project. 20 pp.

Dreschel, P., C. Quansah, and F. Penning De Vries. 1999. Urban and peri-urban agriculture in West Africa: Characteristics, challenges, and need for action. In *Agriculture urbaine en Afrique de l'ouest*. International Development Research Centre (IDRC/CRDI), Online: http://web.idrc.ca/en/ev-33700-201-1-DO_TOPIC.html

Druilhe, C., A. de Guardia, D. Rogeau, and N. le Mouel. 2002. Dynamics of carbon and nitrogen in wastewater sludge composting. Proc Intl Composting and Compost Sci Symposium, Columbus, Ohio: CD ROM.

Eastman, B.R., P.N. Kane, C.A. Edwards, L. Trytek, B. Gunadi, A.L. Stermer, and J.R. Mobley. 2001. The effectiveness of vermiculture in human pathogen reduction for USEPA biosolids stabilization. *Compost Science & Utilization* 9:38-49.

Eckinci, K., H.M. Keener, and D.L. Elwell. 2000. Composting short paper fiber with broiler litter and additives. I. Effects of initial pH and carbon/nitrogen ratio on ammonia emission. *Compost Science & Utilization* 8:160-172.

Edwards, C.A. 1988. Breakdown of animal, vegetable and industrial organic wastes by earthworms. *In* C.A. Edwards and E.F. Neuhauser (eds.) *Earthworms in waste and environmental management*, SPB Academic Publishing, The Hague, 21-31.

----. 1998. The use of earthworms in the breakdown and management of organic wastes. *In* C.A. Edwards (ed.). *Earthworm Ecology*, CRC Press, Boca Raton, FL, 327-354.

Edwards, C.A., I. Burrows, K.E. Fletcher, and B.A. Jones. 1984. The use of earthworms for composting farm wastes. *In* J.K.R. Gasser (ed.) *Composting of agricultural and other wastes*, Elsevier Applied Science Publishers, London.

Eggen, T., and O. Vethe. 2001. Stability indices for different composts. *Compost Science & Utilization* 9:19-26.

Eghball, B. 1999. Liming effects of beef cattle feedlot manure or compost. *Communications in Soil Science & Plant Analysis* 30:2563-2570.

----. 2000. Nitrogen mineralization from field-applied beef cattle feedlot manure or compost*. Soil Science Society of America Journal* 64:2024-2030.

Eghball, B., and J.E. Gilley. 1999/ Phosphorus and nitrogen in runoff following beef cattle manure or compost application. *Journal of Environmental Quality* 28:1201-1210.

Eghball, B., and G.W. Lesoing. 2000. Viability of weed seeds following manure windrow composting. *Compost Science & Utilization* 8:46-53.

Eghball, B., and J.F. Power. 1999a. Composted and non-composted manure application to conventional and no-tillage systems: corn yield and nitrogen uptake. *Agronomy Journal* 91:819-825.

----. 1999b. Phosphorus- and nitrogen-based manure and compost applications: Corn production and soil phosphorus *Soil Science Society of America Journal* 63:895-901.

Eiland, F., A.M. Lind, M. Leth, J.J.L. Iversen, M. Klamer, and H.E.K. Jensen. 2001. C and N turnover and lignocellulose degradation during composting of *Miscanthus* straw and liquid pig manure. *Compost Science & Utilization* 9:186-197.

Elvira, C., L. Sampedro, E. Benitez and R. Nogales. 1998. Vermicomposting of sludges from paper mill and dairy industries with *Eisenia andrei*: a pilot-scale study. *Bioresource Technology* 63:205-211.

Elwell, D.L., Keener, H.M.; Wiles, M.C.; Borger, D.C.; Willett,-L.B. 2001. Odorous emissions and odor control in composting swine manure/sawdust mixes using continuous and intermittent aeration. *Transactions of the American Society of Agricultural Engineers* 44:1307-1316.

Enyong, L.A., S.K. Debrah, and A. Bationo. 1999. Farmers' perceptions and attitudes towards introduced soil-fertility enhancing technologies in western Africa. *Nutrient Cycling in Agroecosystems* 53:177-187.

Epstein, E. 1997. *The Science of Composting*, Technomic Publishing Co, Lancaster, PA, 487 pp.

Eriksen, G.N., F.J. Coale, and G.A. Bollero. 1999. Soil nitrogen dynamics and maize production in municipal solid waste amended soil. *Agronomy Journal* 91:1009-1016.

Esse, P.C., A. Buerkert, P. Hiernaux, and A. Assa. 2001. Decomposition of and nutrient release from ruminant manure on acid sandy soils in the Sahelian zone of Niger, West Africa. *Agriculture, Ecosystems & Environment* 83:55-63.

Evans, D. 1995. Sweet corn nitrogen fertilization. Oswego County Vegetable Program News, Cornell Cooperative Extension.

Evanylo, G.K., and C. Sherony. 2002. Agronomic and environmental effects of compost use for sustainable vegetable production. Proc Intl Composting and Compost Sci Symposium, Columbus, Ohio: CD ROM.

Fieldson, R.S. 1984. The economic feasibility of earthworm culture on animal wastes. *In* J.K.R. Gasser (ed.) *Composting of agricultural and other wastes*, Elsevier Applied Science Publishers, London.

FAOSTAT. Food and Agriculture Organization of the United Nations Statistical Database: http://faostat.fao.org/default.jsp

Fisher, M.G., R.L. Warner, and W.A. Masters. 2000. Gender and agricultural change: Crop-livestock integration in Senegal*. Society & Natural Resources* 13:203-222.

Frederickson, J., K.R. Butt, R.M. Morris and C. Daniel. 1997. Combining vermiculture with traditional green waste composting systems. Soil Biology & Biochemistry 29:725-730.

Frederickson, J., and D. Knight. 1988. The use of anaerobically digested cattle solids for vermiculture. *In* C.A. Edwards and E.F. Neuhauser (eds.) *Earthworms in waste and environmental management*, SPB Academic Publishing, The Hague, 33-47.

Funes, F. 2002. The organic farming movement in Cuba. *In* F. Funes, L. García, M. Bourque, N. Pérez, and P. Rosset (eds.) *Sustainable Agriculture and Resistance: Transforming Food Production in Cuba*, FoodFirst Books, Oakland, CA, 1-26.

Gajalakshmi, S., E.V. Ramasamy, S.A. Abbasi. 2001a. Towards maximising output from vermireactors fed with cow dung spiked paper waste. *Bioresource Technology* 79:67-72.

----. 2001b. Assessment of sustainable vermiconversion of water hyacinth at different reactor efficiencies employing *Eudrilus eugeniae* Kinberg. *Bioresource Technology* 80: 131-135.

Gale, E., D. Sullivan, D. Hemphill, A. Bary, and C. Cooper. 2002. Estimating plant available nitrogen from composted and uncomposted organic materials. Washington State University/Oregon State University Online Research Brief: http://www.soils1.org

Garrec, N., F. Picard-Bonnaud, and A.M. Pourcher. 2003. Occurrence of *Listeria* spp. and *L monocytogenes* in sewage sludge used for land application: effect of dewatering, liming and storage in tank on survival of species. *FEMS Immunology and Medical Microbiology* 356:275-283.

Ghosh, M., G.N. Chattopadhyay and K. Baral. 1998. Transformation of phosphorus during vermicomposting. *Bioresource Technology* 69:149-154.

Gigliotti, G., D. Businelli, and P.L. Giusquiani. 1996. Trace metal uptake and distribution in corn plants grown on a 6-year urban waste compost amended soil. *Agriculture, Ecosystems & Environment* 58:199-206.

Gioacchini, P., A. Nastri, . Marzadori, C. Giovanni, L. Vittori-Antisari, and C. Gessa. 2002. Influence of urease and nitrification inhibitors on N loses from soils fertilized with urea. *Biology & Fertility of Soils* 36:129-135.

Giraddi, R.S. 2000. Influence of vermicomposting methods and season on the biodegradation of organic wastes. *Indian Journal of Agricultural Sciences* 70:663-666.

Gonzalez, R.F., and L.R. Cooperband. 2002. Compost effects on soil physical properties and field nursery production. Proc Intl Composting and Compost Sci Symposium, Columbus, Ohio: CD ROM.

Grabowski, M.A. 2001. Controlled microbial compost and Telone C35 as alternatives to methyl bromide fumigation in annual production of strawberries. MS Thesis, North Carolina State University, Raleigh, NC.

Grandy, A.S., G.A. Porter, and M.S. Erich. 2002. Organic amendment and rotation crop effects on the recovery of soil organic matter and aggregation in potato cropping systems*. Soil Science Society of America Journal* 66:1311-1319.

Grappelli, A., E. Galli, and U. Tomati. 1987. Olive oil wastewaters as fertilizer via vermicomposting. *In* A.M. Bonvicini and P. Omodeo (eds.) *On Earthworms*, Selected Symposia and Monographs U.Z.I., Modena, 419-422.

Gratelly, P., E. Benitez, C. Elvira, A. Polo, and R. Nogales. 1996. Stabilization of sludges from a dairy processing plant using vermicomposting. *In* C. Rodriguez-Barrueco (ed.) *Fertilizers and Environment*, Kluwer Acad Pub, Amsterdam, 323-326.

Graziano, P.L., and G. Casalicchio. 1987. Use of worm-casting techniques on sludges and municipal wastes: development and application. *In* A.M. Bonvicini and P. Omodeo (eds.) *On Earthworms*. Selected Symposia and Monographs U.Z.I., Modena, 459-464.

Guéye, F., F. Ganry, and T. Binh. 1986. Elaboration d'un compost enrichi en phosphate par le phosphate naturel: Etude agronomiqie. Proc Les arbres fixateurs de l'azote: L'amélioration biologique de la fértilité du sol, 19-25 March 1986, Dakar, 473-486.

Gunnarsson, S., and H. Marstorp. 2002. Carbohydrate composition of plant materials determines N mineralization. *Nutrient Cycling in Agroecosystems* 62:175-183.

Hadas, A., T.B. Parkin, and P.D. Stahl. 1998. Reduced CO_2 release from decomposing wheat straw under N-limiting conditions: Simulation of carbon turnover. *European Journal of Soil Science* 49:487-494.

Haimi, J., and V. Huhta. 1986. Capacity of various organic residues to support adequate earthworm biomass for vermicomposting*. Biology & Fertility of Soils* 2:23-27.

Hamilton, D.W., W.G. Luce, A.D. Heald. [No date]. Production and characteristics of swine manure. OSU Extension Facts F-1735, Oklahoma Cooperative Extension Service.

Hand, P., W.A. Hayes, J.E. Satchell, and J.C. Frankland. 1988. The vermicomposting of cow slurry. *In* C.A. Edwards and E.F. Neuhauser (eds.) *Earthworms in waste and environmental management*. SPB Academic Publishing, The Hague, 49-63.

Haque, I., J.M. Powell, and S.K. Ehui. 1995. Improved crop-livestock production strategies for sustainable soil management in tropical Africa. *In* R.Lal and B.A. Stewart (eds.) *Soil Management: Experimental Basis for Sustainability and Environmental Quality*, CRC Press, Boca Raton, FL, 293-344.

House, G.J., and M. del Rosario-Alzugaray. 1989. Influence of cover cropping and no-tillage practices on community composition of soil arthropods in a North Carolina agroecosystem. *Environmental Entomology* 18:302-307.

Howard, A. 1943. *An Agricultural Testament*. Part II: The Indore Process. Oxford University Press, New York, 39-115.

Hubbard, R.K., R.A., Leonard, and A.W. Johnson. 1991. Nitrate transport on a sandy coastal plain soil underlain by plinthite. *Transactions of the American Society of Agricultural Engineers* 34:802-808.

Humpert, C.P. 2000. New trends in sustainable farming build compost use. *BioCycle*, July, 30-33.
Iglesias-Jiménez, E. 2001. Nitrogen availability from a mature urban compost determined by the ^{15}N isotope dilution method. *Soil Biology & Biochemistry* 33:409-412.
Institut Sénégalais de Recherches Agricoles (ISRA). 1995. Plan régional de la Zone Centre-Nord du Bassin Arachidier (CNBA). Commision CNBA, ISRA, Bambey.
Ipke, F.N., J.M. Powell, N.O. Isirimah, T.A.T. Wahua, and E.M. Ngodigha. 1999. Effects of primary tillage and soil amendment practices on pearl millet yield and nutrient uptake in the Sahel of West Africa. *Experimental Agriculture* 35:437-448.
Ishida, F., Tian, G. and T. Wakatsuki. 2001. Indigenous knowledge and soil management. In W.A. Dick and J.L Hatfield (eds.) *Sustaining Soil Fertility in West Africa*, SSSA/ASA, Madison, WI, 91-110.
Jones, D.L. 1999. Potential health risks associated with the persistence of *Escherichia coli* 0157 in agricultural environments. *Soil Use& Management* 15:76-83.
Isse, A.A., A.F. MacKenzie, K. Stewart, D.C. Cloutier, and D.L. Smith. 1999. Cover crops and nutrient retention for subsequent sweet corn production. *Agronomy Journal* 91:934-939.
Jairajpuri, M.S. 1993. Earthworms and vermiculture: an introduction. *In* A.K. Ghosh (ed.) *Earthworm Resources & Vermiculture*. Zoological Survey of India, Calcutta, 1-5.
Jones, D.L. 1999. Potential health risks associated with the persistence of *Escherichia coli* O157 in agricultural environments. *Soil Use & Management* 15:76-83.
Kale, R.D. 1993. Vermiculture: scope for new biotechnology. *In* A.K. Ghosh (ed.) *Earthworm Resources & Vermiculture*. Zoological Survey of India, Calcutta, 105-108.
----. 1998. Earthworms: nature's gift for utilization of organic wastes. *In* C.A. Edwards (ed.) *Earthworm Ecology*, CRC Press, Boca Raton, FL, 355-376.
Kanté, S., and T. Defoer. 1996. How farmers classify and manage their land: implications for research and development activities. *In* A. Budelman (ed.) *Agricultural R & D at the Crossroads: Merging Systems Research and Social Actor Approaches,* Royal Tropical Institute, Amsterdam.
Kaplan, D.L., R. Hartenstein, E.F. Neuhauser, and M.R. Malecki. 1980. Physicochemical requirements in the environment of the earthworm *Eisenia foetida*. *Soil Biology & Biochemistry* 12:347-352.
Karmegam, N., K. Alagumalai, and T. Daniel. 1999. Effect of vermicompost on the growth and yield of green gram (*Phaseolus aureus* Roxb.). *Tropical Agriculture (Trinidad)* 76:143-146.
Keeney, D.R., and D.W. Nelson. 1982. Nitrogen—Inorganic forms. *In* A.L. Page *et al.* (ed.) Methods of Soil Analysis. Part 2., 2nd. Ed., Agron Monographs 9, ASA and SSSA, Madison, WI, 643-698.
King, L.D., J.C. Burns, and P.W. Westerman. 1990. Long-term swine lagoon effluent applications on `Coastal' Bermudagrass: II. Effect on nutrient accumulation in soil. *Journal of Environmental Quality* 13:609-612.
Kirchner, M.J., A.G. Wollum II, and L.D. King. 1993. Soil microbial populations and activities in reduced chemical agroecosystems. *Soil Science Society of America Journal* 57:1289-1295.
Klock-Moore, K.A. 2001. Effect of controlled-release fertilizer application rates on bedding plant growth in substrates containing compost. *Compost Science & Utilization* 9:215-220.
Kouyaté, Z., and A.S.R. Juo. 1998. Effets des engrais verts et des rotations de cultures sur la productivité des sols au Mali. In *Plantes de couverture en Afrique de l'ouest*, International Development Research Centre (IDRC/CRDI), http://web.idrc.ca/en/ev-31927-201-1-DO_TOPIC.html
Kpomblekou, A.K., R.O. Ankumah, and H.A. Ajwa. 2002. Trace and nontrace element content of broiler litter. *Communications in Soil Science & Plant Analysis* 33:1799-1811.
Kroese, R. 2002. Industrial agriculture's war against nature. *In* A. Kimbrell (ed) *Fatal Harvest: The Tragedy of Industrial Agriculture*, Island Press, Washington, 21-27.
Krogh, L. 1997. Field and village nutrient balances in millet cultivation in northern Burkina Faso: a village case study. *Journal of Arid Environments* 35:147-159.
Kumar, K., C.J. Rosen, and S.C. Gupta. 2002. Kinetics of nitrogen mineralization in soils amended with sugar beet processing by-products. *Communications in Soil Science & Plant Analysis* 33:3635-3651.
Kumar, V., and K.P Singh. 2001. Enriching vermicompost by nitrogen fixing and phosphate solubilizing bacteria. *Bioresource Technology* 76:173-175.
Lal, R. 1990. *Soil Erosion in the Tropics: Principles and Management*. McGraw Hill, New York, 590 pp.
Langdale, G.W., R.R. Bruce, and A.W. Thomas. 1987. Restoration of eroded Southern Piedmont land in conservation tillage systems. *In* J.F. Power (ed.) *The Role of Legumes in Conservation Tillage*, Soil Conservation Society of America, 142-143.

Lazarovits, G. 2001. Management of soil-borne plant pathogens with organic soil amendments: a disease control strategy salvaged from the past. *Canadian Journal of Plant Pathology* 23:1-7.

Lazarovits, G., K.L. Conn, and J. Potter. 1999. Reduction of potato scab, verticillium wilt, and nematodes by soymeal and meat and bone meal in two Ontario potato fields. *Canadian Journal of Plant Pathology* 21:345-353.

Leitzinger, C. 2001. The potential of co-composting in Kumasi: Quantification of urban and peri-urban nutrient balance. *In* P. Dreschel and D. Kunze (eds.*) Waste Composting for Urban and Peri-urban Agriculture: Closing the Rural-Urban Nutrient Cycle in Sub-Saharan Africa*, CABI Publishing, New York, 150-162.

Léon, S., G. Villalobos, J. Fraile, and N. González. 1992. Cultivo de lombrices (*Eisenia foetida*) utilizando compost y excretas animales. *Agronomia Costaricense* 16:23-28.

Lievens, B., K. Vaes, J.Coosemans, and J.Ryckeboer. 2001. Systemic resistance induced in cucumber against pythium root rot by source separated household waste and yard trimmings composts. *Compost Science & Utilization* 9:221-229.

Liu, L., J.W. Klopper, and S.Tuzun. 1995. Induction of systemic resistance in cucumber by plant growth-promoting rhizobacteria: Duration of protection and effect of host resistance on protection and root colonization. *Phytopathology* 85:1064-1068.

Locke, T. D. Jones, D. Hollomon, and T. O'Neill. 2001. Fungicide Resistance. Fungicide Resistance Action Group-UK (FRAG-UK), ADAS, Online: www.pesticides.gov.uk

Loehr, R.C., E.F. Neuhauser, and R. Malecki. 1985. Factors affecting the vermistabilization process: temperature, moisture content, and polyculture. *Water Resource Technology* 19:1311-1317.

Ma,Y., N.M. Dickinson, and M.H. Wong. 2002. Toxicity of Pb/Zn mine tailings to the earthworm Pheretima and the effects of burrowing on metal availability. *Biology & Fertility of Soils* 36:79-86.

Mackintosh, M. 1989. *Gender, Class, and Rural Transition: Agribusiness and the Food Crisis in Senegal*, London, Zed Books, 218 pp.

Madejon, E., P. Burgos, J.M. Murilo, and F.Cabrera. 2001. Phytotoxicity of organic amendments on activities of select soil enzymes. *Communications in Soil Science and Plant Analysis* 32:2227-2239.

Malthus, T. 1836. An Essay on the Principle of Population, as it affects the Future Improvement of Society, with Remarks on the Speculations of Mr Godwin, M. Condorcet and Other Writers, 6th Edition. Online: http://www.econlib.org/library/Malthus/malPlong.html

Mamo, M., C.J. Rosen, T.R. Halbach, and J.F. Moncrief. 1998. Corn yield and nitrogen uptake in sandy soils amended with municipal solid waste compost*. Journal of Production Agriculture* 11:469-475.

Mando, A., and R. Miedema. 1997. Termite-induced change in soil structure after mulching degraded (crusted) soil in the Sahel. *Applied Soil Ecology* 6:241-249.

Mando, A., and L. Brussard. 1999. Contribution of termites to the breakdown of straw under Sahelian conditions. *Biology & Fertility of Soils* 29:332-334.

Manna, M.C., P.K. Ghosh, B.N. Ghosh, and K.N. Singh. 2001. Comparative effectiveness of phosphate-enriched compost and single superphosphate on yield, uptake of nutrients and soil quality under soybean-wheat rotation. *Journal of Agricultural Science* 137:45-54.

Manning, R. 2000. *Food's Frontier: The Next Green Revolution*, North Point Press, New York, 240 pp.

Marr, C. 1994. Sweet corn. Kansas State University Horticulture Report. Online: http://www.oznet.ksu.edu/library/hort2/mf669.pdf

Martín-Olmedo, P., and R.M. Rees. 1999. Short-term N availability in response to dissolve-organic-carbon from poultry manure, alone or in combination with cellulose. *Biology & Fertility of Soils* 29:386-393.

Matlon, P.J., and A. A. Adesina. 1997. Agricultural growth and sustainability: Prospects for semi-arid West Africa. *In* S.A. Vosti and T. Reardon (eds.) *Sustainability, Growth, and Poverty Alleviation: A Policy and Agroecological Perspective*, Johns Hopkins University Press, Baltimore, 229-245.

Masciandaro, G., B. Ceccanti, and C. Garcia. 1997. Soil agro-ecological management: Fertirrigation and vermicompost treatments. *Bioresource Technology* 59:199-206.

----. 2000. "In situ" vermicomposting of biological sludges and impacts on soil quality. *Soil Biology & Biochemistry* 32:1015-1024.

Maynard, A.A. 1993. Nitrate leaching from compost amended soils. *Compost Science & Utilization* 1:65-72

----. 2002a. Leaf compost reduces fertilizer use for corn. *BioCycle*, March, 56-59.

----. 2002b. Using compost and cover crops to reduce fertilization requirements in sweet corn production. Proc Intl Composting and Compost Sci Symposium, Columbus, Ohio: CD ROM

Mazzola, M., D.M. Granatstein, D.C. Elfving, and K. Mullinix. 2002. Cultural management of microbial community structure to enhance growth of apple in replant soils. *Phytopathology* 92:1363-1366.

Mbaye, A. 1999. Production des légumes à Dakar: importance, contraintes et potentialités. In *Agriculture urbaine en Afrique de l'ouest*. International Development Research Centre (IDRC/CRDI), http://web.idrc.ca/en/ev-33702-201-1-DO_TOPIC.html

McConnell, D., A. Shiralipour, and W. Smith. 1994. Compost impact on soil/plant properties. In *Composting Source Separated Organics*, JG Press, Emmaus, PA, 89-91.

McInerney, M., and T. Bolger. 2000. Temperature, wetting cycles and soil texture effects on carbon and nitrogen dynamics in stabilized earthworm casts. *Soil Biology & Biochemistry* 32: 335-349.

McLeod, R.V., and R.G. Hegg. 1984. Pasture runoff water quality from application of inorganic and organic nitrogen sources. *Journal of Environmental Quality* 13:122-126.

McVay, K.A., D.E. Radcliffe, and W.I. Hargrove. 1989. Winter legume effects on soil properties and nitrogen fertilizer requirements. *Soil Science Society of America Journal* 53:1856-1862.

Mehlich, A. 1984. Mehlich 3 soil test extractant: A modification of Mehlich 2 extractant. *Communications in Soil Science & Plant Analysis* 15:1490-1516.

Michigan State University (MSU). 2003. The economics of composting. Online: http://www.msue.msu.edu/misanet/Composting/economics_of_composting.htm

Mikkelsen, R.L. 2000. Nutrient management for organic farming: A case study. *Journal of Natural Resources & Life Science Education* 29:88-92

Mitchell, A. 1997. Production of *Eisenia fetida* and vermicompost from feedlot cattle manure. *Soil Biology & Biochemistry* 29:763-766.

Mittal, A. 2002. Giving Away the Farm: The 2002 Farm Bill. Food First/Institute for Food and Development Policy *Backgrounder* 8(3).

Mokolobate, M.S., and R.J. Haynes. 2002. Comparative liming effect of four organic residues applied to an acid soil. *Biology & Fertility of Soils* 35:79-85.

Moll, R.H., E.J. Kamprath, and W.A. Jackson. 1982. Analysis and interpretation of factors which contribute to efficiency of nitrogen utilization *Zea mays*. *Agronomy Journal* 74:562-564

Mollier, A., and S. Pellerin. 1999. Maize root system growth and development as influenced by phosphorus deficiency. *Journal of Experimental Botany* 50:487-497.

Moukam, A., and E.D Tchato. 1987. Utilisation des residus agricoles (parche de café) en vue de l'amélioration de la fertilité de certains sols ferrallitiques en culture continue. *In* International Board for Soil Research and Management (IBSRAM). Land Development and Management of Acid Soils in Africa, Proc IBSRAM session of the first regional seminar on Lateritic Soils, Materials, and Ores, Douala, Cameroon, January 21-27, 1987.

Mueller, J.P., D.A. Pezo, J. Benites, N.P. Schlaepfer. 2001. Conflicts between conservation agriculture and livestock over the utilization of crop residues. *In* L. Garcia-Torres, J. Benites, and A. Martinez-Vilela (eds.) Conservation Agriculture, a Worldwide Challenge. Proc. I World Congress on Conservation Agriculture, Madrid, 1-5 October 2001, FAO/ECAF.

Mukhtar, S., J.L. baker, and R.S. Kanwar. Corn growth as affected by excess soil water. *Transactions of the American Society of Agricultural Engineers* 33:437-442.

NRAES (Natural Resource, Agriculture, and Engineering Service). 1992. *On-Farm Composting Handbook*. NRAES-54, Ithaca, NY, 186 pp..

----. 1999. *Field Guide to On-Farm Composting*. NRAES-114, Ithaca, NY, 118 pp.

National Academy of Sciences. 2002. Biosolids Applied to Land: Advancing Standards and Practices. Ch. 3. Epidemiological Evidence of Health Effects associated with biosolids production and application. http://www.nap.edu/openbook/0309084865/html/106html

Ndegwa, P.M., and S.A. Thompson. 2001. Integrating composting and vermicomposting in the treatment and bioconversion of solids. *Bioresource Technology* 76:107-112.

----. 2000. Effect of C-to-N ratio on vermicomposting of biosolids. *Bioresource Technology* 75:7-12.

Ndegwa, P.M., S.A. Thompson, and K.C. Das. 2000. Effects of stocking density and feeding rate on vermicomposting of biosolids *Bioresource Technology* 71:5-12.

Négri, O. A. 2001. Rapport de Stage: Le site expérimental de Keur Saib Ndoye. Pratiques de maraîchage bio-intensifs. Rodale Institute, Thiés/ Centre de Formation Professionnelle Horticole, Camberène.

Neuhauser, E.F., R.C. Loehr, and M.R. Malecki. 1988. The potential of earthworms for managing sewage sludge. *In* C.A. Edwards and E.F. Neuhauser (eds.) *Earthworms in Waste and Environmental Management*, SPB Academic Publishing, The Hague, 9-20.

Nonnecke, I.L. 1989. *Vegetable Production*. Ch. 14. Sweet Corn. Van Norstrand Reinhold, New York, 415-438.

North Carolina Division of Agriculture and Consumer Services (NCDA & CS). http://www.ncagr.com/stats/

Nova, A. 2002. Cuban agriculture before 1990. *In* F. Funes, L. García, M. Bourque, N. Pérez, and P. Rosset (eds.) *Sustainable Agriculture and Resistance: Transforming Food Production in Cuba*, FoodFirst Books, Oakland, CA, 27-39

Nyborg, M., E.D. Solberg, S.S. Malhi, S. Takyi, P. Yeung, and M. Chaudry. 1991. Deposition of anthropogenic sulfur dioxide on soils and resulting acidification. *Developments in Plant & Soil Science* 45:147-156.

Oluwasemire, K.O., C.J. Stigter, J.J. Owunubi, and S.S. Jagtap. 2002. Seasonal water use and water productivity of millet-based cropping systems in the Nigerian Sudan savanna near Kano. *Agricultural Water Management* 56:207-227.

Oppenheim, S. 2001. Alternative agriculture in Cuba. *American Entomologist 47*:216-227.

Ouédraogo, S., and M.K.Bertelsen. The value of research on indigenous knowledge: preliminary evidence from the case of zai in Burkina Faso. *Journal of Sustainable Agriculture* 10:33-41.

Ouédraogo, E., A. Mando, and N.P. Zombré. 2001. Use of compost to improve soil properties and crop productivity under low input agricultural systems in West Africa. *Agriculture, Ecosystems & Environment* 84:259-266.

Oyer, L.J., and J.T. Touchton. 1990. Utilizing legume cropping systems to reduce nitrogen fertilization requirements for conservation-tilled corn. *Agronomy Journal* 82:1123-1127.

Ozores-Hampton, M., and C.S. Vavrina. 2002. Worm castings: an alternative to sphagnum peat moss in organic tomato *(Lycopersicon esculentum* Mill.) transplant production. Proc Intl Composting and Compost Sci Symposium, Columbus, Ohio: CD ROM.

Paredes, C., A. Roig, M.P. Bernal, M.A. Sanchez-Monedero, and J. Cegarra. 2000. Evolution of organic matter and nitrogen during co-composting of olive mill wastewater with solid wastes. *Biology & Fertility of Soils* 32:222-227.

Pascual, J.A., C. Garcia, T. Hernandez, and M. Ayuso. 1997. Changes in the microbial activity of an arid soil amended with urban organic wastes. *Biology & Fertility of Soils* 24:429-434.

Payne, W.A., J.H. Williams, K.A. Mai-Moussa, and R.D. Stern. 1998. Crop diversification in the Sahel through the use of environmental changes near *Faidherbia albida* (Del.). *Crop Science* 38:1585-1591.

Peacock, A.D., M.D. Mullen, D.B. Ringelberg, D.D. Tyler, D.B. Hedrick, P.M. Gale, and D.C. White. 2001. Soil microbial community responses to dairy manure or ammonium nitrate applications. *Soil Biology & Biochemistry* 33:1011-1019.

Perfecto, I. 1994. The transformation of Cuban agriculture after the cold war. *American Journal of Alternative Agriculture* 9:98-108.

Perucci, P., S. Dumontet, S.A. Bufo, A. Mazzatura, and C. Casucci. 2000. Effects of organic amendment and herbicide treatment on soil microbial biomass *Biology & Fertility of Soils* 32: 17-23.

Petersen, S.O., A.M. Lind, and S.G. Sommer. 1998. Nitrogen and organic matter losses during storage of cattle and pig manure. *Journal of Agricultural Science* 130:69-79.

Phillips, V.R. 1988. Engineering problems in the breakdown of animal wastes by earthworms. *In* C.A. Edwards and E.F. Neuhauser (eds.) *Earthworms in Waste and Environmental Management*, SPB Academic Publishing, The Hague, 111-118.

Poore, M., J. Green, G., Rogers, K. Spivey, and K. Dugan. 2000. Nitrate Management in Beef Cattle. North Carolina Cooperative Extension Service publication: http://www.cals.ncsu.edu/an_sci/extension/animal/nutr/nitrate%20management%20in%20beef.pdf

Powell, J.M., F.N. Ipke, and Z.C. Somda. 1999. Crop yield and the fate of nitrogen and phosphorus following application of plant material and feces to soil. *Nutrient Cycling in Agroecosystems* 54:215-226.

Pretty, J.N. 1995. *Regenerating Agriculture: Politics and Practice for Sustainability and Self-Reliance*, Joseph Henry Press, Washington, 320 pp.

Pretty, J. 2002. *Agri-Culture: Reconnecting People, Land, and Nature,* Earthscan Publications, London, 261 pp.

Ranells, N.N., and M.G. Wagger. 1992. Nitrogen release from crimson clover in relation to plant growth stage and composition. *Agronomy Journal* 84:424-430.

----. 1997. Nitrogen-15 recovery and release by rye and crimson clover cover crops. *Soil Science Society of America Journal* 61:943-948.

Raviv, M., Y. Chen, and Y. Inbar. 1986. Peat and peat substitutes as growth media for container-grown plants. *In* Y. Chen and Y. Avnimelech (eds) *The Role of Organic Matter in Modern Agriculture*, Martinus Nijhoff Publishers, Dordecht, 257-287.

Reider, C., R. Janke, and J. Moyer. 1991. Compost Utilization for Field Crop Production. Technical Report submitted to the Pennsylvania Energy Office, Rodale Institute, Kutztown, PA.

Reider, C.R., W.R. Herdman, L.E. Drinkwater and R. Janke. 2000. Yields and nutrient budgets under composts, raw dairy manure and mineral fertilizer. *Compost Science & Utilization* 8:328-340.

Reinecke, A.J., and J.M. Venter. 1985. Influence of moisture on the growth and reproduction of the compost worm *Eisenia fetida* (Oligochaeta). *Review of Ecology & Biology of Soil* 22:473-481.

----. 1987. Moisture preferences, growth and reproduction of the compost worm *Eisenia fetida* (Oligochaeta). *Biology & Fertility of Soils* 3:135-141.

Rodale Institute (RI). 1989. Soil Degradation and Prospects for Sustainable Agriculture in the Peanut Basin of Senegal, RI, Emmaus, 86 pp.

-----. 1990. Rapport annuel, CRAR-Rodale Senegal, Thiès.

-----. 1994. Rapport annuel 1991-1992, CRAR-Senegal/Rodale International, Thiès.

-----. 1994. Nëballeen ngir seen mbay gëne naat! Faîtes du compostage pour régénerer vos sols et augmenter vos récoltes, L'Institut Rodale, Thiès, 17 pp.

-----. 1997. Etude d'impact des activités de Rodale, RI, Thiès.

-----. 1998. Rapport technique NRBAR (VB-521), RI, Thiès.

-----. 2002a. Projet Vanderbilt, Rapport Annuel 2001-2002, RI, Thiès.

-----. 2002b. Projet Vanderbilt, Situation Année I, Draft, RI, Thiès.

-----. 2003. Vanderbilt Project, Annual Report 2002-2003, RI, Thiès.

Roose, E., and B. Barthès. 2001. Organic matter management for soil conservation and productivity restoration in Africa: a contribution from Francophone research. *Nutrient Cycling in Agroecosystems* 61:159-170.

Rosset, P. 2001. Genetically Engineering Crops: Will they feed the hungry and reduce poverty? *LEISA Magazine*, December, 6-8.

Sagar, D.V., S.N. Naik, and P. Vasudevan. 2002. Vermicomposting of kitchen waste and its effect on the quality and quantity of essential oil of *Ocimum sanctum* L. Proc Intl Composting and Compost Sci Symposium, Columbus, Ohio: CD Rom.

Salinas-Garcia, J.R., F.M. Hons, J.E. Matocha, and D.A. Zuberer. 1997. Soil carbon and nitrogen dynamics as affected by long-term tillage and nitrogen fertilization. *Biology & Fertility of Soils* 25:182-188.

Sanchez, J.E., T.C. Wilson, K. Kizilkaya, E. Parker, and R.R. Harwod. 2001. Enhancing the mineralizable nitrogen pool through substrate diversity in long term cropping systems. *Soil Science Society of America Journal* 65:1442-1447.

Sánchez-Monedero, M.A., A. Roig, C. Paredes, and M.P. Bernal. 2001. Nitrogen transformation during organic waste composting by the Rutgers system and its effects on pH, EC and maturity of the composting mixtures. *Bioresource Technology* 78:301-308.

Sarr, D., and D. Diallo. 2003. Rapport du Mission d'Evaluation des Resultats et Impacts du Projet d'Agriculture Regénératrice en Zone Pluviale (PAREP) à Koumpentoum. Rodale Institute, Thiès.

Sarr, M., C. Agbogba, A. Russel-Smith, and D. Masse. 2001. Effects of soil faunal activity and woody shrubs on water infiltration in a semi-arid fallow of Senegal. *Applied Soil Ecology* 16:283-296.

Sartaj, M., L. Fernandes, and N.K. Patni. 1997. Performance of forced, passive, and natural aeration methods for composting manure slurries. *Transactions of the American Society of Agricultural Engineers* 40:457-463.

Scheidtweiler, T.W., and K.H. Kromer. 1996. Tillage and planting methods to control wind erosion in the semi-arid tropics. *In* B. Buerkert, B.E. Allison and M. van Oppen (eds.) Proc Int'l Symposium "Wind Erosion in West Africa: The Problem and Its Control", University of Hohenheim, Germany, 5-7 December 1994.

Senapati, B.K. 1993a. Earthworm gut contents and its significance. *In* A.K. Ghosh (ed.) *Earthworm Resources & Vermiculture*, Zoological Survey of India, Calcutta, 97-99.

----. 1993b. Vermitechnology in India. *In* A.K. Ghosh (ed.) Earthworm Resources & Vermiculture. Zoological Survey of India, Calcutta, 109-111.

Sène, M., and P.M. Guéye. 1998. Test de variétés améliorées avec des amendements organiques et phosphatés en parcelles paysannes dans le terroir de Ndoff. Rapport annuel projet V13 ISRA/Rodale/NRBAR Campagne 1997, Rodale Institute, Thiès.

Senehoun, J., F. Heidhues, and D. Deybe. 1999. Structural adjustment program and soil erosion: a bio-economic modeling approach for northern Benin. *In* D.E. Stott, R.H. Mohtar, and G.C. Steinhardt (eds.) *Sustaining the Global Farm*. Selected Papers from the 16th International Soil Conservation Organization Meeting, May 24-29, Purdue University, 131-138.

Sherman-Huntoon, R. 2000. Latest developments in mid- to large-scale vermicomposting. BioCycle, November, 51-54.

Shi, W., J.M. Norton, B.E. Miller, and M.G. Pace. 1999. Effects of aeration and moisture during windrow composting on the nitrogen fertilizer value ofdairy manure composts. *Applied Soil Ecology* 11:17-28.

Shuman, L.M. 1998. Effect of organic waste amendments on cadmium and lead in soil fractions of two soils. *Communications in Soil Science and Plant Analysis* 29:2939-2952.

Shuman, L.M., S. Dudka, and K. Das. 2002. Cadmium forms and plant availability in compost-amended soil. *Communications in Soil Science and Plant Analysis* 33:737-748.

Sikora, L.J., and V. Yakovchenko. 1996. Soil organic matter mineralization after compost amendment. *Soil Science Society of America Journal* 60:1401-1404.

Sims, J.T., and D.C. Wolf. 1994. Poultry waste management: Agricultural and environmental issues. *Advances in Agronomy* 52:1-83.

Singh, C.P, and A. Amberger. 1995. The effect of rock phosphate-enriched compost on the yield and phosphorus nutrition of rye grass. *American Journal of Alternative Agriculture* 10:82-87.

Sligh, M. Organics at the Crossroads: The past and future of the organic movement. *In* A. Kimbrell (ed) *Fatal Harvest: The Tragedy of Industrial Agriculture*, Island Press, Washington, 341-345.

Slingerland, M., and M. Masdewel. 1996. Mulching on the Central Plateau of Burkina Faso. In C. Reij, I. Scoones and C. Toulmin (eds.) *Sustaining the Soil: Indigenous Soil and Water Conservation in Africa*, Earthscan Publications Ltd., London.

Slingerland, M.A., and V.E. Stork. 2000. Determinants of the practice of zai and mulching in north Burkina Faso. *Journal of Sustainable Agriculture* 16:53-77.

Slocum, K. 2002. Proc Start Your Own Worm Farm, North Carolina State University, Raleigh, NC.

Stone, A.G. 2002. Organic matter-mediated suppression of *Pythium*, *Phytophthera*, and *Aphanomyces* root rots in field soils. Proc Intl Composting and Compost Sci Symposium, Columbus, Ohio: CD Rom.

Subler, S. 2002. Proc Start Your Own Worm Farm, North Carolina State University, Raleigh, NC.

Subler, S., C. Edwards, and J. Metzger. 1998. Comparing vermicomposts and composts. BioCycle , July, 63-66.

Sullivan, D.M., A.I. Bary, D.R. Thomas, S.C. Fransen, and C.G. Cogger. 2002. Food waste compost effects on fertilizer nitrogen efficiency, available nitrogen, and tall fescue yield. *Soil Science Society of America Journal* 66:154-161.

Szczech, M., W. Rondomanski, M.W. Brzeski, U. Smolinska, and J.F. Kotowski. 1993. Suppressive effect of a commercial earthworm compost on some root infecting pathogens of cabbage and tomato. *Biological Agriculture & Horticulture* 10:47-52.

Tarkalson, D.D., V.D. Jolley, C.W. Robbins, and R.E. Terry. 1998. Mycorrhizal colonization and nutrient uptake of dry bean in manure and compost manure treated subsoil and untreated topsoil and subsoil. *Journal of Plant Nutrition* 21:1867-1878.

Tawalar, S., and R.E. Rhoades. 1998. Scientific and local classification and management of soils. *Agriculture & Human Values* 15:3-14.

Taylor-Powell, E., A. Manu, S.C. Geiger, M. Ouattara, and A.S.R. Juo. 1991. Integrated management of agricultural watersheds: Land tenure and indigenous knowledge of soil and crop management. TropSoils Bulletin 91-04. SM CRSP, Raleigh, NC.

Tester, C.F. 1990. Organic amendment effects on physical and chemical properties of a sandy soil. *Soil Science Society of America Journal* 54:827-831.

Thomsen, I.K. 2001. Recovery of nitrogen from composted and anaerobically stored manure labeled with ^{15}N. *European Journal of Agronomy* 15:31-41.

Tillman, R.W., and A. Surapaneni. 2002. Some soil-related issues in the disposal of effluent on land. *Australian Journal of Experimental Agriculture* 42:225-235.

Tiquia, S.M., T.L. Richard, and M.S. Honeyman. 2002. Carbon, nutrient, and mass loss during composting. *Nutrient Cycling in Agroecosystems* 62:15-24.

Tiquia, S.M., N.F.Y. Tam, L.J. Hodgkiss. 1996. Microbial activities during composting of spent pig manure sawdust litter at different moisture contents. *Bioresource Technology* 55:201-206.

Tomati, U., E. Madejon, and E. Galli. 2000. Evolution of humic acid molecular weight as an index of compost stability. *Compost Science & Utilization* 8:108-114.

Treto, E., M. García, R.M. Viera, and J.M. Febles. 2002. Advances in Organic Soil Management. *In* F. Funes, L. García, M. Bourque, N. Pérez, and P. Rosset (eds*.) Sustainable Agriculture and Resistance: Transforming Food Production in Cuba*, FoodFirst Books, Oakland, 164-189.

Tschakert, P. 2001. Human dimensions of carbon sequestration: A political ecology approach top soil fertility management and desertification control in the Old peanut Basin. *Aridlands Newsletter* 49. Online: http://ag.arizona.edu/OALS/ALN/aln49/tschakert.html

Tuitert, G., M. Szczech, and G.J Bollen. 1998. Suppression of *Rhizoctonia solani* in potting mixtures amended with compost made from organic household waste. *Phytopathology* 88:764-773.

van der Ploeg, R.R., W. Böhm, and M.B. Kirkham. 1999. On the origin of the theory of mineral nutrition of plants and the Law of the Minimum. *Soil Science Society of America Journal* 63-1055-1062.

Villenave, C., T. Bongers, K. Ekschmitt, P. Fernandes, and R. Oliver. 2003. Changes in nematode communities after manuring in millet fields in Senegal. *Nematology* 5:351-358.

Vincelas-Akpa, M. and M. Loquet. 1997. Organic matter transformations in lignocellulosic waste products composted or vermicomposted (*Eisenia fetida andrei*): chemical analysis and ^{13}C CPMAS NMR spectroscopy. *Soil Biology & Biochemistry* 29:751-758.

Viteri, S.E., and E.L. Schmidt. 1996. Ecology of indigenous soil rhizobia: Selective response of *Bradyrhizobium japonicum* to a soybean meal. *Applied Soil Ecology* 3:187-195.

Wagger, M.G. 1989. Time of desiccation effects on plant composition and subsequent nitrogen release from several winter annual cover crops. *Agronomy Journal* 81:236-241.

Wang, F.L., and A.K. Alva. 2000. Ammonium adsorption and desorption in sandy soils. *Soil Science Society of America Journal* 64:1669-1674.

Warman, P.R., and M.J. AngLopez. 2002. The chemical properties of vermicompost derived from different feedstocks. Proc Intl Composting and Compost Sci Symposium, Columbus, Ohio: CD Rom.

Webb, P., and D.L. Coppock. 1997. Prospects for pastoralism in semi-arid Africa. *In* S.A. Vosti and T. Reardon (eds.). *Sustainability, Growth, and Poverty Alleviation: A Policy and Agroecological Perspective*, Johns Hopkins University Press, Baltimore, pp. 246-260.

Wei, G., J.W. Kloepper, and S. Tuzun. 1996. Induced systemic resistance to cucumber diseases and increased plant growth by plant-growth promoting rhizobacteria under field conditions. *Phytopathology* 86:221-224.

Weil, R.R., and S.K. Mughogho. 1993. Nutrient cycling by *Acacia albida* (sin. *Faidherbia albida*) in agroforestry systems. ASA Special Publication 56:97-108.

Werner, M., and J.R. Cuevas. 1996. Vermiculture in Cuba. BioCycle ???(6):60-62.

Westley, K. 1997. Women, men, and manure: An analysis of soil fertility, crop yields and wealth and gender interactions in a soil restoration project in northern Senegal. Unpublished research paper submitted to Yale School of Forestry and Environmental Studies, New Haven.

Wezel, A., and R. Bocker. 1999. Mulching with branches of an indigenous shrub (*Guiera senegalensis*) and yield of millet in semi-arid Niger. *Soil Tillage Research* 50:341-344.

Wezel, A., and T. Rath. 2002. Resource conservation strategies in agro-ecosystems of semi-arid West Africa. *Journal of Arid Environments* 51:383-400.

White, S. 1996. Vermiculture bioconversions in India. *BioCycle*, June, 65.

Wiles, M.C., J.C. Amburgey, D.L. Elwell, H.M. Keener, D.C. Borger, and L.B. Willett. 2001. Volatile fatty acid emission during composting of swine waste amended with sawdust as a measure of odor potential. *Compost Science & Utilization* 9:27-38.

Williams, T.O. 1999. Factors influencing manure application by farmers in semi-arid West Africa. *Nutrient Cycling in Agroecosystems* 55:15-22.

Wong, M.T.F., S. Nortcliff and R.S. Swift. 1998. Method for determining acid ameliorating capacity of plant residue compost, urban waste compost, farmyard manure, and peat applied to tropical soils. *Communications in Soil Science & Plant Analysis* 29:2927-2937.

Wong, S.H., and D.A. Griffiths. 1991. Vermicomposting in the management of pig-waste in Hong Kong. *World Journal of Microbiology & Biotechnology* 7:593-595.

Yermiyahu, U., R. Keren, and Y. Chen. 2001. Effect of composted organic matter on boron uptake by plants. *Soil Science Society of America Journal* 65:1436-1441.

Zaharah, A.R., A.R. Bah, N.K. Mwange, P. Kathuli, and P. Juma. 1999. Management of Gliricidia (*Gliricidia sepium*) residues for improving sweet corn yield in an ultisol. *Nutrient Cycling in Agroecosystems* 54: 31-39.

Zaongo, C.G.L., C.W. Wendt, R.J Lascano and A.S.R. Juo. 1997. Interactions of water, mulch and nitrogen on sorghum in Niger. *Plant & Soil* 197: 119-126.

Zhou, L.X., and J.W.C. Wong. 2001. Effect of dissolved organic matter from sludge and sludge compost on soil copper sorption. *Journal of Environmental Quality* 30:878-883.

<u>Appendix</u>: Interview guide for Peanut Basin farmers and GIEs

A. Local soil and land classification

1. What are the types of soil here and where are they found?

    Quelles sont les types de sol et où sont-ils trouvés ?
    Yan xeetu suuf ngeen gis fii ki gox bi?

2. How do you distinguish them?

    Comment est-ce que vous les distinguez ?
    Naka ngeen leen di rañale ?

3. Which are the most fertile?

    Quelles sont les plus fertiles ?
    Yan suuf moo gënë naat ?

4. What makes the soil fertile?

    Qu'est-ce que rend les sols fertiles ?
    Lan mooy dundal suuf si?

5. How do you recognize that a soil is fertile?

    Comment reconnaissez-vous qu'un sol est fertile ?
    Naka ngeen di xame ne suuf si naat na ?

6. (If soil is not fertile) How do explain that a soil is no longer fertile (last five years)?

    (Depuis cinq ans) comment expliquez-vous que le sol n'est plus fertile ?
    Ci juróómi at ci gannaw, naka la seen suuf soppiko ? Naka la nééw doole ?

7. What are the indicators of a reduction in soil fertility ?

    Quelles sont les indications de la diminution de la fertilité du sol ?
    Naka ngeen di xame ne seen suuf nééw na doole ?

B. Crops

1. What crops do you plant in each soil ?

    Qu'elles cultures plantez-vous dans chaque sol ?
    Ban xeetu gancax ngeen di ji ci suufu jóór? Ci deg jóór ? Ci deg ? Ci xur ?

2. Who decides this ?

    Qui le décide ?
    Kan moo koy dogal ?

3. What is the rotation ?

    Qu'est-ce que la rotation ?
    Naka ngeen di jalarbe gancax gi ?

4. Do you fallow your fields ?

    Laissez-vous vos champs en jachères?
    Ndax dangeen booyal seeni tool ?

5. How long are they fallow?

    Pendant combien de temps sont-ils en jachères ?
    Ñaata at ngeen di booyal tool bi ?

6. Has this period grown shorter over the last five years ?

    Est-ce que cette période est devenue plus courte au cours des années ?
    Ay at ci gannaw ndax diiru boyyal nu mu daan tolu ?

C. Residues

1. What do you do with crop residues after harvest ?

    Qu'est-ce que vous faites avec les déchets de culture après la récolte ?
    Lan ngeen di def ag mbalit miy des ci tool yi ?

2. When you collect millet stalks, do you select only those that are useful, or take them all back to separate at home?

    Quand vous ramassez les tiges, sélectionnez-vous seulement celles qui sont utiles ou bien ramenez-vous tous pour les séparer à la maison ?
    Bu ngeen di dajale gatax yi, dangeen di jël yu baax yi wàlla yëpp ngeen di yobbu ci kër gi ?

Appendix (cont'd)

3. Do you leave the roots in the ground when you remove crop residue?
   Laissez-vous les racines dans la terres quand vous enlevez les résidues ?
   Su ngeen di dajale mbalit mi ci tool bi, ndax dangeen di bàyyi reenu gatax yi ci suuf si walla dangeen koy buddi ?
4. Who does this work ?
   Qui fait ce travail ?
   Kan mooy def liggééy boobu ?
5. Do you burn your fields? Why or why not?
   Brûlez-vous les champs ? Pourquoi ou pourquoi pas ?
   Ndax dangeen di taal seeni tool ? Lu tax ?

D. Fertilization

1. How do you determine which crop needs to be fertilized?
   Comment est-ce que vous déterminez quelle culture doit être fertilisée ?
   Ban gancax ngeen di def angare?
2. Does this depend on the type of soil?
   Est-ce que cela dépend sur le type du sol ?
   Ndax ci xeetu suuf bi ngeen di tënku ?
3. When soil fertility has declined, what do you do?
   Lors que la fertilité du sol a baissé, qu'est-ce que vous faîtes ?
   Bu suuf si newee doole, lan ngeen di def ?
4. Do you use synthetic fertilizer? Why or why not?
   Utilisez-vous les engrais chimiques ? Pourquoi ou pourquoi pas ?
   Ndax angare ngeen di jëfëndikoo ? Lu tax ?
5. Do you use rock phosphate? Why or why not?
   Utilisez-vous la phosphate de fond ? Pourquoi ou pourquoi pas ?
   Ndax fosfaat ngeen di jefendikoo ? Lu tax ?

E. Manure

1. How do you collect manure?
   Comment ramassez-vous le fumier ?
   Fan ngeen di jëe neefare? Naka ngeen di koy inde?
2. How do you stock it?
   Comment le stockez-vous ?
   Naka ngeen di koy dence?
3. How long do you stock it before using it?
   Combien de temps est-ce vous le stocker avant que vous l'utilisiez ?
   Ban diir bala ngeen koy jëfëndikoo ?
4. Do you add anything to it before using it ? Do ou turn it? Water it? Cover it ?
   Est-ce vous ajoutez quelque chose au fumier avant que vous l'utilisiez ? Est-ce que vous le ratournez ? Arrosez ? Couvriez ?
   Dangeen di yokk dara ? Ndax dangeen di jaxase jal bi? Ndax dangeen koy roose ? Ndax dangeen koy muur ?
5. Who does this work ?
   Qui fait ce travail ?
   Kan mooy def liggééy bi ?
6. If you have a limited quantity of manure, where do you use it? Does it depend on the crop? The soil?
   Si vous avez une quantité limité de fumier, où est-ce que vous le mettez ? Est-ce que cela dépend sur la culture ? Le sol ?
   Bu ngeen amee tuuti neefare rekk, naka ngeen koy tas tool bi?
7. Are there some manures that are better than others? Why?
   Est-ce qu'il y a certains fumiers meilleurs que d'autres ? Pourquoi ?
   Ban neefare moo gene baax ? Lu tax ?

Appendix (cont'd)

8. How do you transport the manure to your fields ? How do you apply it?

Comment transportez-vous le fumier aux champs ? Comment le appliquez-vous ?
Naka dangeen di yobbu neefare bi ci tool yi ? Naka ngeen koy tase ?

F. Compost

1. Survey those who currently compost
Sondage de ce qui fait et utilise le compost au présent
Ñan ñooy def kompos ci grupmaan bi ? Ci dëkk bi ?
2. Why do you use compost ?
Pourquoi utilisez-vous le compost ?
Lu tax ngeen di jëfëndikoo kompos bi ?
3. Why is compost good ? How is it good ?
Pourquoi est-il bon le compost ? Comment est-il bon ?
Lu tax kompos bi am solo ? Naka la amee solo ?
4. Why don't you use compost ?
Pourquoi est-ce que vous n'utilisez pas le compost ?
Ndax am na ñu du jëfëndikoo kompos ? Lu tax ?

G. Labor

1. Who does the field work? (ask men and women separately)
Qui fait le travail aux champs ? (demandez aux hommes et aux femmes séparément)
Kan mooy liggééy ci tool yi ?
2. Planting ? Cultivating ? Harvesting ?
La semence ? La cultivation ? La récolte ?
Kan mooy ji ? Kan mooy bey? Kan mooy góób?
3. Who does the gardening ?
Qui fait le maraîchage ?
Kan mooy def mbeyu noor ?
4. Planting ? Cultivating ? Harvesting ?
La cultivation ? L'arrosage ? La récolte ?
Kan mooy bey ? Kan mooy roose? Kan mooy góób?
5. How do you organize the *sase* (group labor)?
Comment est-ce vous organisez le sase ?
Naka ngeen di doxale ki sase liggééy ?
6. Are you paid if you work in someone else's field?
Est-ce que vous êtes remboursés si vous traveillez dans le champs de quelqu'un d'autre ?
Ndax dinañu léén sas liggééy ?
7. Do you pay those who work in your field?
Est-ce vous remboursez ceux qui travaillez dans vos champs ?
Ndax dangeen sase seen liggééy tool ?

H. Land tenure

1. Who owns the land you work?
Qui possède les champs que vous travaillez ?
Kan mooy moom tool yi ngeen di liggééy ?
2. How did you get it?
Comment est-ce que vous les avez eus ?
Nan ngeen def ba am tool yi ?