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Grain amaranth production and effects of soil amendments in Uganda

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ABSTRACT

Grain amaranths (*Amaranthus* spp.) are high protein content and quality pseudo-cereal crops originally domesticated in Latin America whose favorable nutritional profile belies their potential to alleviate nutrition and food insecurity in developing countries. Grain amaranth was introduced as a nutrient dense food into the Kamuli District, eastern Uganda, in 2006 through Iowa State University's Center for Sustainable Rural Livelihoods (CSRL) in conjunction with Ugandan partners Volunteer Efforts for a Development Concerns (VEDCO), a local non-governmental organization (NGO), and Makerere University. Initial analysis of protein content of amaranth grain pooled from farms in the Kamuli District indicated protein levels from 11.7% to 12.5%, lower than the average value of 15% found in the literature.

A study was therefore designed to determine: 1) common production practices for grain amaranth in Uganda; 2) variability of amaranth grain yields and protein content between farms; 3) variability of amaranth grain yields and protein content between varieties; and 4) the effects of soil physical and chemical properties, and the use of organic soil amendments, on amaranth grain yields and protein content.

A non-random snowball survey of amaranth-growing farms in the Kamuli District was conducted in June 2009 to determine common agronomic practices and use of soil amendments. Soil samples to a depth of 15 cm were also taken to determine soil physical and chemical properties of amaranth fields in the area. Survey results indicated that grain amaranth is grown over variable demographic and geographic ranges within the Kamuli district. Farmers reported growing amaranth on small plots, which had previously supported a wide range of crops. Amaranth was most frequently grown in pure stands, with "golden" as

the most common variety. Pest pressure was generally moderate to low in severity. Most respondents did not use organic soil amendments to improve crop yields, but the majority of those who applied amendments used cow manure. Soil amendments were variable in residue age and management practices.

On-station grain amaranth trials were conducted in the Wakiso District, 18 km north of Kampala in south-central Uganda, to test effects of poultry manure and composted manure applied at 0, 1, 1.5, and 3 ton ha^{-1} on amaranth yield and protein content. Three identical experiments were conducted in this regard (Experiments 1–3), with two reported here, due to accidental destruction of the amaranth crop in Experiment 1. Experiment 2 was conducted during the dry season beginning on 17 July 2009 and harvested on 9 October 2009 (91 DAP), with data collected on amendment nutrient composition, seedling establishment, plant height, leaf number, insect and weed populations, grain yield and protein content. Mean grain yields for Experiment 2 were 1110 kg ha^{-1} (SD: 66 kg ha^{-1}) with no significant differences between treatments, but yields for “cream” (1013 kg ha^{-1}) and “golden” (1208 kg ha^{-1}) were significantly greater than those for ‘Plainsman’ (191 kg ha^{-1}) (P=0.0083). Amaranth grain was pooled across all treatments and varieties in Experiment 2 to determine a mean protein content of 14.5% (SD: 0.2%).

Experiment 3 was conducted during the rainy season and planted on 3 October 2009, with harvest occurring on three different dates in late December 2009 and early January 2010 (80 – 98 DAP). Data was taken for all parameters listed above for Experiment 2. Mean amaranth grain yields for Experiment 3 were 1886 kg ha^{-1} (SD: 921.1 kg ha^{-1}), with no significant differences between treatments, but yields for “cream” (2750 kg ha^{-1}) were significantly greater than those for “golden” (1742 kg ha^{-1}) and ‘Plainsman’ (1166 kg ha^{-1})

(P=0.0043). Grain yields were also significantly greater for Column 3 (2724 kg ha^{-1}) than for Column 1 (1709 kg ha^{-1}). Pooled amaranth grain across all treatments and varieties in Experiment 3 contained a mean protein content of 15.1% (SD: 0.2%)

On-farm experiments were conducted during the short rainy season of 2009 in the Kamuli District to determine the effects of cattle manure applied at 27 ton ha^{-1} on "cream" and "golden" amaranth varieties compared to a control treatment (0 ton ha^{-1}). Ten farms participated in the experiment; data on soil physical and chemical properties, planting and harvest date, plant height, plant density, plant health and disease parameters, qualitative weather assessments, and grain yield were collected. Yields were significantly different between farms, with a maximum reported yield of 1230 kg ha^{-1} and a minimum of 239 kg ha^{-1}. Application of cattle manure provided a significant yield increase, where treatment averages were 667 kg ha^{-1} where soil amendments were utilized, compared to 420 kg ha^{-1} in control plots, representing a yield increase of 58.6% with the addition of cattle manure.

There were no significant differences between varieties, with a mean of 619 kg ha^{-1} for "cream" and 468 kg ha^{-1} for "golden" varieties (SD: 487 kg ha^{-1} and 261 kg ha^{-1}, respectively). Amaranth grain protein content was significantly different between farms, ranging from 12.1% to 15.1%. Average protein content of 14% across treatments and varieties revealed a greater amaranth protein content than previously reported for the Kamuli District. Linkages with organic associations, such as NOGAMU (National Organic Agriculture Movement of Uganda, Kampala, Uganda), can help facilitate marketing strategies for amaranth farmers whose production exceeds family needs and who desire to enter commercial markets.

CHAPTER 1: LITERATURE REVIEW AND THESIS ORGANIZATION

Grain Amaranth

Grain amaranth belongs to the cosmopolitan *Amaranthus* genus of some 60 species (NRC, 1972), which also includes the vegetable amaranths and other species suitable for cultivation as forage and ornamental use (Brenner et al., 2000). All the cultivated amaranths are considered underutilized crops and have, until recently, received little research attention. However, grain amaranths and many other *Amaranthus* species show tremendous potential for human consumption and other uses, and are particularly promising as a remedy for hunger and malnutrition in developing countries (NRC, 1972).

Amaranth grain maintains a high protein content, averaging 15 grams per 100 grams dry weight (moisture content of about 10% for whole grain) across the three cultivated species, and compares well with conventional grains. For example, wheat, maize, and rice average a protein content of 14, 9, and 7%, respectively (Senft, 1979).

More than quantity, amaranth grain is remarkable for its protein quality, maintaining high levels of the essential amino acid lysine, along with uncommon sulfur-containing amino acids like methionine and cysteine. The diets of the malnourished are often deficient in lysine and grain amaranth's amino acid constitution closely approximates the standard protein recommended by the FAO/WHO for optimum human nutrition (Senft, 1979).

History of Amaranth

The earliest prehistoric evidence of grain amaranth's domestication comes from an archeological dig at a cave in the Tehuacán Valley, in the modern southeast Mexican state of

Puebla. Seeds of *Amaranthus cruentus* found in the caves were dated as 6,000 years old, while seeds identified as *A. hypochondriacus* were dated as 3,500 years old (Sauer, 1993). However, both species were likely domesticated earlier. Coincidentally, caves of the Tehuacán Valley also recorded the first archeological evidence of maize (*Zea mays*) domestication (10,000 y.a.) (Benz and Long, 2000).

Both maize and amaranth grain domestication occurred, at least partially, in south-central Mexico but, like that of maize, the historical domestication of grain amaranth is contentious and poorly understood. It has been widely hypothesized that *Amaranthus hybridus*, which has a wide modern distribution in multiple habitats throughout the Americas, was the progenitor of *A. cruentus* (Sauer, 1993). *Amaranthus hypochondriacus*, on the other hand, displays characteristics of both *A. cruentus* and the wild species *Amaranthus powelli*, and may be a hybrid of the two (Sauer, 1993). A third species of grain amaranth, *Amaranthus caudatus*, appears to have originated in the Andean region of South America, and may represent a hybrid between a pre-historic introduction of *A. cruentus* and a local wild species. Archaeological evidence for the time and place of original *A. caudatus* domestication has yet to be uncovered (Sauer, 1993). Also, historical reconstruction of amaranth use based on the pollen record has proved difficult due the similarity between amaranth and chenopod pollen in the presumed area of origin (Tsukada, 1967).

Recent studies have probed the phylogenetic origins of the grain amaranths, often using molecular techniques. One such study yields support for a monophyletic origin of all three species from *A. hybridus* based on common genetic markets. However, this investigation had a low number of samples, many of which were not from the presumed area(s) of origin (Chan and Sun, 1997). Other studies generally confirm origination from *A.*

hybridus, but demonstrate a closer relationship between *A. caudatus* and *A. hypochondriacus* than either to *A. cruentus* (Brenner et al., 2000).

The Aztec civilization of central Mexico represents the first recorded instance of grain amaranth use and the crop figured prominently in Aztec culture. Grain amaranth was a staple of importance on par with maize and beans, and records indicate that large quantities of amaranth (~20,000 tons) were collected from 17 provinces as tribute to the ruling class at Tenochtitlan (modern Mexico City) (NRC, 1972; Brenner et al., 2000).

Amaranth, which the Aztecs called ‘huautli’, was grown as a complement to maize, with amaranth as a long-season (180+ days to harvest) and maize as a short-season crop (Gordon, 1980). Probably, this was done largely to distribute labor over time; however, grain amaranth proteins have an excellent amino acid profile which, when combined with maize, would approximate the modern standard protein recommended by the FAO/WHO (Senft, 1980). Harvested grains were then used in beverages, sauces, certain special types of tortilla, and a variety of medicinal applications (Brenner et al., 2000).

Not surprisingly, grain amaranth achieved symbolic importance in Aztec culture and was an important component of religious rituals and other occasions. The grain was popped or ground by Aztec women and mixed with honey and other sweet, adhesive foods, then molded into various forms (including animals, natural features, and gods) for consumption at ceremonies of all scales (NRC, 1972; Brenner et al., 2000). Controversially, one of the materials added to the aforementioned mixture may have been human blood; despite the known Aztec custom of human sacrifice, whether blood was associated with the figures is unclear (NRC, 1972).

According to this line of argument, the association of amaranth with blood, along with human sacrifice and other Aztec customs appalled the Spanish conquistadors upon their conquest of the Aztecs in the early 1500s (NRC, 1972). Therefore, when the Spanish attempted to suppress Aztec culture and religion, amaranth production and consumption was discouraged accordingly. However, according to Spanish missionaries, grain amaranth use as food and in traditional cultural practices continued at a reduced level until some 50 years after the Spanish conquest but subsequently declined (Early, 1992).

Though grain amaranth has continued to be produced as a minor crop in remote areas of the Americas until modern times, it was spread to the Old World during the Columbian exchange along with other New World flora, possibly inadvertently (Brenner et al, 2000; NRC, 1972). The history of grain amaranth's diffusion into the Old World is unclear; however, *A. hypochondriacus* was reported in European gardens as an ornamental plant during the 1500s, and was in use as a minor crop in Russia and Eastern Europe by the 1700s (NRC, 1972).

Grain amaranth was presumably introduced from these points of origin to Asia and Africa by the early 1800s. *Amaranthus hypochondriacus* grew in popularity in Asia during this time period, and found a particular niche in the northern Indian sub-continent, where it is grown at high altitudes (Joshi and Rana, 1991; Sauer, 1967; Sauer, 1993). As of the mid-1990s, South Asia was the world's only region where grain amaranth production was increasing (Brenner et al, 2000).

Western scientists largely ignored grain amaranth's agricultural potential until the 1970s, taking interest only after new evidence revealed grain amaranth protein to be of high quality (Senft, 1979). During this time, key promoters like Robert Rodale devoted substantial resources to amaranth research and development, with amaranth production increasing in the United States during the 1980s and 1990s. Improved U.S. cultivars of *A. hypochondriacus* are now grown commercially, mostly as a niche product for the health food market (Brenner et al., 2000).

Grain Amaranth Production

All members of the genus *Amaranthus* are dicotyledonous warm-season annuals. The amaranths have historically been cultivated within 30 degrees of the equator, but are adapted to a wide variety of growing conditions (Brenner et al., 2000; Putnam, 1990). Like maize and sugarcane, all amaranths utilize the C4 photosynthetic pathway for energy production and grain amaranth tends to grow best in hot, dry climates (Brenner et al., 2000). Daily high temperature should be at least 21° C for optimal amaranth growth, while optimal temperatures for germination range from 16° to 35° C, with seedling emergence expedited at the upper end of this spectrum (Joshi and Rana, 1991; NRC, 1972). The C4 pathway conveys a degree of drought tolerance which, in tandem with the capacity to prevent wilting and death through osmotic adjustment (Graham et al., 2006; Kigel, 1994; NRC, 1972), permits grain amaranth to grow in regions with less than 200 mm annual precipitation (Putnam, 1990).

Drought tolerance may also be conveyed to grain amaranth by its indeterminate flowering habit, as well as a long taproot and extensive lateral root system (Johnson and Henderson, 2002; Putnam, 1990). Research in North Dakota by Johnson and Henderson (2002) indicats that grain amaranth typically responds to soil moisture stress by increasing root depth and extracting soil water from deeper in the soil profile.

Despite its tropical origins, certain varieties have become adapted to variations in day length at higher latitudes (Putnam, 1990). *A. hypochondriacus* is the species commonly grown in the United States. *A. cruentus* displays the least photoperiod-sensitivity and is thus the most widely-adapted of the three. Similarly, there are few restrictions to amaranth production at high elevation, but only *A. caudatus* performs well at elevations more than 3000m above sea level. Amaranths are not frost tolerant and plant growth is truncated at around 8° C. Temperatures below 4° C result in injury (Putnam, 1990).

Despite the foregoing desirable characteristics, agricultural production of grain amaranth can be problematic in industrialized agricultural systems in temperate latitudes. One major problem in both temperate and tropical areas is grain amaranth's propensity for lodging that results in the breaking of the stalk or even uplifting of the roots and collapse of the entire plant. In temperate areas, excessive levels of nitrogen exacerbate this issue by increasing plant height, while in the tropics, intensity of precipitation is often the cause of lodging (Brenner et al., 2000; Putnam, 1990).

Most amaranth cultivars exhibit considerable variability in important traits such as plant height and seed head size, with plants in the same field often contrasting dramatically in these features. Further, amaranth maintains a fair degree of phenotypic plasticity in response to the growing environment and is subject to self-thinning and "self-suppressing" that preclude complete development of individual plants. "Self-suppression" typically reduces yields in stunted plants (Brenner et al., 2000; Myers, 1996).

Amaranth seeds are quite small and range from 0.7 to 0.9 g per 1000 seeds, often leading to poor and non-uniform seedling establishment (Brenner et al., 2000; Putnam, 1990). This problem may be rectified to an extent through cultural practices such as high seeding rates and assuring good seed-to-soil contact at a planting depth of no more than about 2 cm (Baltensperger et al., 1990; Joshi and Rana, 1991). Therefore, establishment represents a crucial growth stage for grain amaranth production because amaranth seedlings are slow-growing relative to weed competitors (Baltensperger et al., 1990; Putnam, 1990).

Grain amaranth water requirements are also highest for seedling establishment and early vegetative growth phases and care should be taken to assure seeds are planted into a moist seedbed (Baltensperger et al., 1990; Joshi and Rana, 1991; NRC, 1984). For example, Johnson and Henderson (2002) demonstrated the importance of adequate soil moisture during establishment and early vegetative stages, while also indicating that high soil moisture during establishment tends to inhibit deep root penetration and vegetative growth but not grain yield. Further, a number of studies have examined the water requirements and drought tolerance of grain amaranths, with most of these corroborating that amaranth water requirements are highest in early growth stages, but that grain amaranths perform well under high temperatures and reduced moisture during later growth phases (Chaudhari et al., 2009; Johnson and Henderson, 2002; Joshi and Rana, 1991; Mng'omba et al., 2002; Piha, 1995).

As alluded to above, weeds represent a major problem in nearly all amaranth production systems and manual weeding or cultivation may be required multiple times during the growing season (Baltensperger et al., 1990; Putnam, 1990). Tarnished leaf bug (*Lygus lineolaris* P. Beauv.) is considered the greatest pest of amaranth globally, damaging plants through its sucking action on meristematic tissue and developing floral buds, blossoms and embryos (Brenner et al., 2000; Joshi and Rana, 1991; Myers, 1996). Other important insect pests include various caterpillars, spider mites (*Tetranychus* spp.), stem weevils, and stem borers(Joshi and Rana, 1991). Pathogens are also relatively rare but can include damping off, stem rot, leaf blight, white rust, and a number of viral infections (Brenner et al., 2000; Joshi and Rana, 1991).

Amaranth grain yields reported in the literature exhibit a large degree of variability depending on such factors as soil chemical and physical properties, climate, planting density, planting time, variety, and level of fertilization. Although most studies containing data on amaranth grain yield do not include information on soil chemical and physical properties, a study in the Kisumu District of western Kenya near Lake Victoria demonstrated yields of 50 kg ha^{-1} at a cattle manure application rate of 0.5 ton ha^{-1}; 110 kg ha^{-1} at 1 ton ha^{-1}; 250 kg ha^{-1} at 2 ton ha^{-1}; and 1500 kg ha^{-1} at 3 ton ha^{-1} (Nyankanga, pers. comm.).

Another Kenyan study by Gupta et al. (1992) in assessing the impact of variety, date of planting, days to maturity, season (‘long’ or ‘short’ rains), planting density, and fertilization on amaranth grain yields at four locations in Kenya found amaranth grain yields ranging from 70.7 to 714.0 kg ha^{-1} at a planting density of 66,666 plants/ha (70 cm between rows, 20 cm within rows). In this experiment, synthetic fertilizer was applied at rates of 21 kg N ha^{-1} and 53 kg P_2O_5 ha^{-1}. Medium-maturing varieties in this study, with maturity dates similar to the “cream” and “golden” varieties in Uganda, tended to have higher yields compared to early- and late-maturing varieties under standardized conditions at Kabete, where yields ranged from 290 kg ha^{-1} to 1020 kg ha^{-1} for early-maturing varieties.

Gupta et al. (1992) also tested the effects of planting date on two high yielding, early- to medium-maturing *A. hypochondriacus* varieties, named ‘1023’ and ‘1024.’ Yields tended to decrease with a later planting date, as ‘1023’ yielded 1157.1 and 1481.6 kg ha^{-1} when planted during the first and second week of the short rains, respectively, while ‘1024’ yielded between 1171.6 and 1484.1kg ha^{-1} for the same periods. These experiments were again standardized with synthetic fertilizer at application rates of 21 kg N ha^{-1} and 53 kg P_2O_5 ha^{-1}.

Yields for the two varieties in absence of synthetic fertilization were tested during the short rains at Kabete, with plots receiving either the standard 21 kg N ha^{-1} and 53 kg P_2O_5 ha^{-1} or no fertilizer (control). Fertilized plots of both ‘1023’ and ‘1024’ yielded 2500 kg ha^{-1}, while unfertilized plots demonstrated yields of 800 kg ha^{-1} for ‘1023’ and 1000 kg ha^{-1} for ‘1024’.

In the study conducted by Olaniyi (2007) in southwest Nigeria, amaranth yields were generally low. Depending on year and variety, grain yields from the study ranged from 400 to 1500 kg ha^{-1}.

In the US, amaranth grain yields typically range from 700 kg ha^{-1} to 1700 kg ha^{-1}, while higher yields have been achieved internationally. Grain amaranth breeding programs in Latin America have achieved yields of 7200 kg ha^{-1} and 4600 kg ha^{-1} for certain varieties in Peru and Mexico, respectively (Brenner et al., 2000).

Center for Sustainable Rural Livelihoods’ Amaranth Efforts

Iowa State University’s Center for Sustainable Rural Livelihoods (CSRL) is a “unique effort dedicated to providing leadership and support that help alleviate hunger and poverty in developing countries.” In cooperation with the Ugandan non-government organization, Volunteer Efforts for Development Concerns (VEDCO), and Kampala-based Makerere University, the CSRL confronts the complex problems of malnutrition and poverty with an agriculturally focused and multi-disciplinary approach that ultimately endeavors to improve the livelihoods of smallholder, subsistence farmers in three sub-counties and six parishes in the Kamuli District of eastern Uganda.

As detailed by Sseguya (2006), malnutrition constitutes a major problem in Kamuli, resulting from factors related to poverty, food insecurity, and lack of knowledge. Malnutrition is manifested through high rates of stunting and low body weight, as well as wasting. The former two parameters are slightly lower in Kamuli than the national average at 35.4% and 22.5%, respectively, while levels of wasting are slightly higher at 4.3% (UBOS and ORC Macro, 2001). Further problems related to health and nutrition include access to potable water, appropriate sanitation, and associated diseases (Sseguya, 2007).

As such, CSRL/VEDCO exclusively promotes nutrient dense foods and expedited the introduction of grain amaranth to Ugandan farmers in 2006. Surveys indicated that 21% of the population was already growing grain amaranth during 2006, while by 2007 the percentage had jumped to 76% (Sseguya, 2007). Another survey conducted by VEDCO in early 2007 indicated that amaranth was grown by diverse groups of people, notably among marginalized groups such as HIV/AIDS patients.

Probably because of its novelty, grain amaranth had found relatively few uses in the Kamuli District as of 2007; the most common practice was to mill the harvested grains, either at a commercial milling location or in the home using mortar and pestle. The flour thereby obtained is typically utilized for home consumption, but may also be sold for between 2500 and 3000 Ugandan shillings (USh) per kilogram. Unprocessed raw seeds sell for between 500 and 2500 USh per kilogram (Nabakabya, 2007).

Grain amaranth flour is almost always combined with other more traditional staples like cassava, maize, millet, and sorghum to create porridges and poshos (stiff porridge). Proportions of ground amaranth and exact recipes for these dishes exhibit considerable intra-household differences. Alternatively, raw grain may be “popped” using a fire-heated pan; popped grains are consumed as is, or used in various admixtures, almost always as a companion to tea. Grains that fail to pop are called “toasted” and are subsequently milled into a fine paste, along with either groundnuts or sesame; the paste is either consumed by itself or functions as a spread on foods like bread or cassava (Nabakabya, 2007).

The surveyed population claims many benefits to growing and consuming grain amaranth. Amaranth is used as a general source of nutrition, for treating various sicknesses (notably HIV/AIDS), increasing physical strength, and as a substitute for milk, particularly during child-weaning (Nabakabya, 2007). In addition to the nutritional benefits accrued via consumption of amaranth grain, amaranth plants may also be consumed as a leaf vegetable after thinning or following harvest of grain (Chapter 2, this document).

Effects of Soil Amendments on Amaranth Yield and Protein Content

Research conducted by VEDCO at Makerere University (Kampala, Uganda) showed protein content of seeds from the two amaranth varieties in Uganda to be 11.7% and 12.5%, far below the 15% average protein content reported in the literature. Bressani (1994) provides an overview of the possible causes of variation in protein content, and attributes differences mainly to genetic variation within and between species, environmental factors (availability of nutrients and soil moisture), and cultural practices.

Low protein content of Uganda amaranth grain may be due to low levels of soil nutrients, particularly nitrogen. As such, low soil fertility associated with land degradation is widely reported and often cited as major constraint to sustainable development throughout sub-Saharan Africa (SSA) (Nyombi et al., 2006). Numerous studies have examined nutrient budgets of nitrogen, phosphorus and potassium in African soils (Esilaba et al., 2005), and Smaling et al. (1997) estimated nutrient loss in SSA at 60-100 kg ha^{-1} yr^{-1}, leading to a nutrient imbalance between -14 to -136 kg ha^{-1} yr^{-1}. The already low nutrient levels of SSA's highly-weathered soils have been exacerbated by nutrient removal due to harvest and losses to runoff and erosion (Kaizzi et al., 2007).

Land degradation in SSA represents a complex, multi-faceted phenomenon with manifold causes that vary by location and scale (Nyasimi, 2006). However, in the Kamuli District, the problem of land degradation is due to factors associated with, "population pressure and poor land use practices, cultivation of fragile lands (swamps and forest areas), and bush burning and deforestation. Resulting from the situation is a downward spiral of productivity, land degradation and poverty" (Sseguya, 2007). The CSRL and VEDCO have therefore endeavored to make improving natural resource management a cornerstone of their intervention among Kamuli farmers (Sseguya, 2007).

There are a number of studies examining the effects of fertilization on grain amaranth yield and protein content (Bressani et al., 1987; Elbehri et al., 1993; Myers, 1998; Olaniyi, 2007). Most studies found a significantly positive correlation between increasing fertilizer application, typically N, and yield with applications of up to 90 kg N ha^{-1} (Myers, 1998). Response of protein content to fertilizer application has been inconsistent, and may depend on environmental factors along with initial levels of plant available nutrients (Pospisil, 2006).

However, few of these studies explored organic soil amendments as a nutrient source, nor did they test amaranth responses in nutrient-poor soils. Additionally, most studies did not report initial plant available nutrient levels prior to fertilizer application.

Notable exceptions include Apaza-Gutierrez et al. (2002), who tested yield response of *A. caudatus* and *A. hypochondriacus* to application of dried organic sheep manure (7.5 and 15 ton ha^{-1}) in Bolivian soils with moderate levels of organic matter and low levels of N-P-K (values not reported). Both species showed a linear yield response to organic and chemical fertilizers and a quadratic response to a mixture of the two. Yield response to fertilization by chemical fertilizer was 29% greater than for the manure treatment.

Another study conducted in Croatia by Pospisil et al. (2006) examined the effects of chemical N fertilizer on grain amaranth yield and protein content, finding a yield response in dry years, but no effect on protein content. On this basis, the authors concluded that organic production of grain amaranth was a possibility in soils where moisture is adequate for provision of plant available N. Further, organic grain amaranth production has proved successful, as evidenced by commercially available organic amaranth grain in the developed world.

Plant Production under Organic Farming Conditions

Organic agriculture offers great promise to farmers in the developed world, but particularly in lesser developed countries, such as Africa, where synthetic inputs (e.g., fertilizers and pesticides), disallowed under organic rules, are not commonplace, due to cost prohibitions and limited access. Transgenic crops, often referred to as genetically modified organisms ("GMOs") in popular literature, also are prohibited in organic agriculture, and currently, have not been widely available in Africa. The basis for GMO prohibition in organic production is both environmental and philosophical, and it is unlikely that the prohibition will be lifted anytime in the foreseeable future (Delate et al., 2006). Based on consumer resistance to purchasing and consuming foods that include GMO ingredients, many US, Japanese, and European Union (EU) food processors require the use of non-GMO ingredients in their products. Consumer resistance to GMO ingredients is higher in the EU and Japan than the US; however, US consumers, like their Japanese and EU counterparts, desire a labeling scheme indicating whether a product contains GMO ingredients. Absent a label, the only way for a consumer to be confident a product does not have GMO ingredients is to purchase products for which there are no GMO ingredients possible or purchase certified organic products. Communicating all aspects of the fast-changing GMO dynamic is critical to consumers' understanding of how GMO prohibition dovetails with the organic system approach to production and concomitant environmental concerns.

There are two levels of organic farming in Africa, certified organic production and non-certified or agro-ecological farming, which is basically the same method of farming practiced since the inception of agriculture in Africa (Parrott et al., 2006). African farmers have a tremendous opportunity to capitalize on the demands for non-GMO foods, particularly for export to the EU, because of their history and knowledge of organic practices (Howden, 2008). In addition, environmental benefits ascribed to organic production include lessening farmer exposure to harmful pesticides; decreased leaching of rapidly mobile sources of nitrogen into groundwater supplies; and recycling local nutrient sources (e.g., livestock manure and plant residue composting) for plant production. It is this final benefit that constitutes a major challenge in tropical agricultural areas, where soil fertility is limited and animals are considered a luxury in extremely poor communities.

In light of the opportunities presented by organic agriculture in Africa, certified organic farming has increased dramatically in recent years to encompass an area of almost 0.9 million ha, representing about 0.11% of the total agricultural area in Africa as of 2007. However, as a percentage, Africa accounts for only about 3% of the global total of organic land by continent (Willer and Yussefi, 2007). As of 2001, statistics indicated that the majority of organic land in Africa was farmed by smallholders, with approximately 730,000 farmers on 700,000 ha (Hine and Pretty, 2007). Uganda had the highest number of organic farmers in Africa in 2007, estimated at 40,000 farmers on 122,000 ha. Uganda ranks third internationally in the number of certified organic farmers, behind Mexico and Italy (Willer and Yussefi, 2007).

Uganda's relatively well-developed organic sector is indicative of a broader trend for certified organic agriculture in Africa, as East and Southern Africa maintain more developed organic sectors than the rest of the continent, with East Africa in the process of developing its own organic standards through the East African Organic Product Standards. As discussed above, the majority of certified organic agriculture is geared toward export production for the European market, as few African countries have well-developed domestic markets for organic products (Parrot et al., 2006; Willer and Yussefi, 2007).

Organic agriculture in Africa has also generated a fair amount of interest from international non-governmental organizations due its cross-cutting benefits in the areas of income-generation, poverty reduction, and environmental sustainability. Since most organic production is generated by geographically dispersed smallholder farmers who are unable to pay for certification, high transaction costs for certification represent a major problem in the African context. As such, donor support and/or cooperation with NGOs is often necessary to facilitate smallholder certification. This has led to the development of a number of innovations for smallholder certification, mainly focused on group certification schemes. The Internal Control System (ICS), which involves annual or semi-annual farm inspection by company-trained local field specialists, is the most prominent example of such a program (Bolwig et al., 2009; Willer and Yussefi, 2007)

Plant Availability of Nutrients from Soils and Organic Soil Amendments

Given that poor soil fertility across Africa constitutes a major constraint for increasing organic production, a review of factors influencing soil nutrition and the role of organic soil amendments is presented to provide context for the thesis research. There are seventeen elements required by all life on earth; of these, the productivity of the world's ecosystems, including agricultural ecosystems, is probably influenced more by deficiencies or excesses of nitrogen (N) than any other element, particularly in the tropics. As the major constitutive element of amino acids and proteins, nitrogen is an essential element in the biological functioning of all forms of life on Earth. In higher plants, nitrogen plays an integral role in photosynthesis, carbohydrate use, and metabolic processes through various plant secondary compounds (Brady and Weil, 1999).

Nitrogen, generally speaking, becomes plant available only after it has entered the soil solution as nitrate (NO_3^--N) or ammonium (NH_4^+-N) ions. Nitrogen enters and exits the soil solution through the microbially-mitigated processes of mineralization and immobilization, respectively. Particularly important in this regard are the array of microorganisms responsible for the process of ammonification, whereby organic N components are converted from immobilized, organically-bound forms associated with soil organic matter (SOM) and plant decaying materials to the mineral form of ammonium. Subsequently, populations of soil autotrophic bacteria are responsible for conversion, or nitrification, of ammonium ions to nitrate (Sylvia et al., 2004).

As such, these processes are responsible for determining plant availability of N and other plant nutrients from soils and organic amendments. Immobilization and mineralization, in turn, depend on a number of interrelated factors, including the physical and chemical properties of organic materials, along with environmental variables such as moisture and temperature (Brady and Weil, 1999).

Environmental factors affecting nitrogen availability

Soil moisture. Soil moisture is an important controlling factor for the mineralization of nitrogen from soils and amendments. The activities of soil microorganisms responsible for nitrogen mineralization are inhibited at both very high and very low soil moisture content, with N uptake by higher plants following a similar pattern (Brady and Weil, 1999; Sylvia et al., 2004). Nitrogen mineralization, therefore, maintains a variable response to soil moisture; however, studies indicate that the greatest amount of mineralization occurs when the soil is at or near field capacity (-10 kPa) and decreases with drying (Griffin and Honeycutt, 2000; Eghball et al., 2002; Olayinka, A., 2003). Although, studies by Calder (1957) and Semb and Robinson (1969) indicate that mineralization may occur at pressures as high as 1500 kPa (15 bars) in certain well-aggregated soils.

The alternating of wet and dry seasons and the attendant flux in precipitation and soil moisture represents the most important controlling factor for N mineralization and plant availability in the tropics. Particularly, as purported by Birch (1960, 1964), mineralization of both organic carbon (C) and nitrogen fractions is accelerated by wetting and drying of soils compared to continuous or stable soil moisture. The foregoing research also demonstrated that alternate wetting and drying cycles differentially increased the rate C mineralization over N mineralization, resulting in lower C:N ratios. Similarly, alternate wetting and drying increased the C:N ratio threshold over which mineralization ceases, thus increasing mineralization rates.

Similarly, mineral nitrogen undergoes major seasonal fluctuations in tropical soils due to the wetting and drying cycle. Mineral nitrogen, particularly nitrate, tends to accumulate in the upper soil profile during the dry season, while the onset of the wet season brings about a brief increase or “flush” of mineral N. This “flush” is usually followed rapidly by a decrease in soil mineral N that endures for the remainder of the wet season (Birch, 1960; Birch, 1964). These phenomena result from a number of factors, including microbial cell lyses during the dry season, the aforementioned capacity for N mineralization to continue at high soil moisture tensions in certain soils (Semb and Robinson, 1969), and movement of mineral nitrogen-bearing water upward in the soil profile due to capillary action during the dry season (Sanchez, 1976).

Soil temperature. The response of soil microbial activity to temperature, as well as other biochemical reactions, may be described by the Q10 parameter, which measures change in the rate of a given reaction for every 10°C change in temperature. Soil microbial activities follow a skew-right distribution at the community level, as microbes are often inactive at low temperatures (0 to 10°C), but activities increase exponentially up to a maximum of 45-50° C. However, denaturation and interference of certain biochemicals begins between 40 and 70°C and most cellular components (i.e., proteins, lipids, and nucleic acids) usually begin to lose structural integrity at temperatures upwards of 100°C (Luo and Zhou, 2006).

However, tropical soils are typically characterized by minimal fluctuations in temperature between seasons. As such, temperature rarely limits microbial activity and, subsequently, mineralization under tropical conditions (Sanchez, 1976).

Soil and amendment physical properties affecting nitrogen availability

Soil and amendment physical properties, such as texture, exert a variable impact on mineralization, depending on a number of exogenous factors. Particularly, some studies indicate a positive relationship between mineralization and the proportion of silt and clay in the soil fine fraction (Watts et al., 2010; Sanchez, 1976). This occurs largely due to the increased soil water holding capacity and soil moisture associated with smaller-sized particles, thus providing moisture for microbial metabolic activities (Sanchez, 1976). As alluded to above, mineralization can occur at high moisture tensions in certain tropical soils.

However, whether this pattern holds appears to depend on the partitioning of soil organic matter between biologically active and protected fractions. Research by Plante et al. (2006) on the impact of soil texture on soil organic matter (SOM) chemical and physical fractioning indicates that clay and silt content is positively correlated with larger quantities of protected SOM. However, such assertions have been countered, as a study by Trumbore (2000) demonstrated that while temperate soils are often dominated by older, more recalcitrant forms of SOM, in tropical soils the younger and more active SOM fraction tends to predominate. Similarly, biochemical protection and, thus, accumulation and mineralization of SOM may be different between soil macroaggregates and microaggragates (Plante et al., 2006; Six et al., 2000).

Such differences between temperate and tropical soils may, in part, be explained by variation in clay mineralogy, given that tropical soils tend to exhibit more variability in clay mineralogy than temperate soils. Certain types of clay, such as smectite and allophone, have been shown to inhibit nitrification and mineralization due to stabilization and protection of organic matter associated with the formation of tightly-bound organo-clay complexes (Brady and Weil, 1999; Hassink, 1997; Wattel-Koekkoek et al., 2001)**.**

As discussed by Sanchez (1976), in tropical soils where layer silicate clay mineralogical systems predominate, such as Entisols, Vertisols, Aridisols, and Mollisols, properties and dynamics associated with ion exchange processes are similar to those found in temperate regions. In large part, this is due to the absence of large quantities of iron and aluminum oxides characteristic of the oxide mineralogical systems associated with tropical Oxisols, Ultisols, and Alfisols. Ion exchange in oxide mineralogical systems is highly variable and dependent on pH, ion concentrations, and pH at the zero point of charge (Sanchez, 1976). In turn, differences in ion exchange processes between and among oxide systems exert a major impact on plant nutrient availability. Particularly, leaching losses of nitrate in tropical soils are controlled by the distribution of macro- and micropores, as well as anion and cation exchange capacity, with higher AEC typically reducing nitrate leaching losses (Sanchez, 1976; Kinjo and Pratt, 1971).

Thus, although soil texture may not be a particularly good predictor of N mineralization, under tropical conditions one might expect the trend of higher mineralization in tropical soils (portending more active cycling of SOM) to hold true, but the opposite under temperate conditions. The foregoing line of reasoning appears to be borne out in the literature, as studies on temperate soils report both negative and positive trends between clay and silt content (Griffin and Honeycutt, 2001; Kooijman et al., 2009; Watts et al., 2010). A study by Mubarak et al. (2001) found that mineralization of crop residues applied to tropical soils was not significantly different between soils of different textures.

Regarding physical properties of soil amendments, there seems to be consensus that the C:N ratio, as discussed below, does not adequately characterize mineralization potential and is limited in evaluating the extent to which amendment nutrients will be mineralized or immobilized (Nahm, 2005). The nature and particle size of amendment materials plays a key role in determining mineralization, as amendments high in lignin tend to be resistant to degradation and large particles are usually more recalcitrant than small particles (Brady and Weil, 1999; Sylvia et al., 2004). Lignin:N ratio, therefore, has been proposed as an improved predictive indicator of mineralization in this regard; however, particle size may also constitute an important factor, as better contact within residues and between residues and the soil surface facilitates more rapid mineralization (Nahm, 2005).

Soil and amendment chemical properties affecting nitrogen availability

pH. There have been a number of studies examining the impact of pH on N mineralization from soils and soil amendments. In general, such research reports a positive correlation between pH and mineralization rates due to inhibition of microbial activity, notably that of nitrifying bacteria, at low pH (Sylvia et al., 2004). For example, a study by Ste-Marie and Paré (1999) examining the effects of vegetation, pH, and N availability on nitrification corroborates that nitrification is suppressed at low pH, finding no net nitrification occurring below pH 4.5. Further, the lower limit for autotrophic nitrification in forest systems appears to exist between pH values of 4.0 and 4.7 (Sahrawat, 1982; De Boer et al., 1989). Similar results were reported by Sierra (2006) and Huang and Chen (2009), the former under tropical conditions. Furthermore, reductions in mineralization at low pH seem to be exacerbated where C:N ratios are high (Ste-Marie and Paré, 1999).

Carbon/nitrogen ratio. The impact of the carbon to nitrogen (C:N) ratio on mineralization from soils and soil amendments has been widely studied. The C:N ratio affects plant nutrient availability primarily through its impact on soil microbial activities. As soil microbes require both carbon and nitrogen nutrition at a ratio of approximately 8:1 (depending on the specific organism), soils or soil amendments with high C:N ratios engender a scarcity of N relative to C. As such, C:N ratios higher than between 20:1 and 25:1 may lead to immobilization of N through incorporation into microbial cells and, thus, reduce N available to plants. Soils and soil amendments with C:N ratios below these values portend N mineralization and increased plant availability (Brady and Weil, 1999; Sylvia et al., 2004).

For soil A horizons, where SOM tends to be high, C:N ratios usually range between 8:1 and 15:1, with a median value of about 12:1. A C:N ratio for sub-soils is typically lower than for topsoils (Brady and Weil, 1999). Although somewhat contentious, meta-analysis of SOM and C:N ratios by Sanchez (1976) indicates that values for these parameters are similar between tropical and temperate soils, with the distribution of SOM essentially the same within the soil profile under natural vegetation. However, cultivation of soils in the tropics disrupts this equilibrium, with losses of SOM due to increases in erosion, as well as decomposition rates associated with tillage-induced changes in soil temperature and aeration (Sanchez, 1976).

For organic soil amendments, the C:N ratio, along with nutrient composition and quality more broadly, is highly variable. Quality of manure-derived amendments depends on the animal species, housing and rearing management, feed, and subsequently climate, and manure storage and handling (Eghball et al., 2002; Davis et al., 2002; Lekasi et al., 2003). The C:N ratio for manure is generally quite low and reportedly ranges anywhere from 1 to 27:1 for poultry manure (Bitzer and Sims, 1988), while cattle manure C:N ratios in the US were reported by Burger and Venterea, 2007) as 11.3 for liquid dairy manure and 17.2 for solid dairy manure. These values are lower than those reported in developing countries. A study by Lekasi et al. (2003) indicated in a survey of cattle manure use among 281 farmers in Central Kenya that the mean C:N ratio for cattle manure was 23.1 with a standard deviation of 9.7 and minima and maxima of 5.3 and 81.0, respectively.

Composting. Composting of organic materials for application as soil amendments comes with both advantages and disadvantages from a nutrient management perspective. In general, the composting process results in lower C:N ratios and higher nutrient concentrations, depending on the length of the composting process and pile management, as much of the initially present carbon and nitrogen is lost to respiration and volatilization (Brady and Weil, 1999; Eghball, 2000; Sylvia et al., 2004). As such, composted material may maintain similar C:N ratios to that of uncomposted manures and other organic materials, generally between

14:1 and 20:1; however, the composting process creates more stabilized organic compounds resembling humus in chemical properties (Brady and Weil, 1999; Diacono and Montemurro, 2009; Eghball, 2000).

Although the predominance of stabilized organic compounds in composted material reduces nitrogen mineralization and availability in the year of application, compost use has numerous ulterior benefits, such as improving handling characteristics due to reduced weight and volume, as well as the elimination of weed seeds and pathogens (Brady and Weil, 1999; Eghball, 2000). Similarly, the long-term benefits of compost application have been well-studied. Despite potentially low N availability from compost in the year of application, repeated application of composted material can increase soil organic nitrogen by up to 90%, thus providing mineralizable N for future growing seasons (Diacono and Montemurro, 2009).

Storage of nitrogen in organic form results in the slow release of inorganic N throughout the growing season, thus allowing for greater synchronization of N availability with a crop demand (Delate and Cambardella, 2004; Diacono and Montemurro, 2009). This synchronization is especially important in organic agricultural systems and the subject of continuing research in this regard (Myers et al., 1994). Repeated application of composted materials, as well as organic amendments more generally, can improve soil physical properties through increases in aggregate stability and CEC, while decreasing soil bulk density (Diacono and Montemurro, 2009).

Factors affecting amendment quantity and quality. In the United States, poultry litter is considered one of the best organic fertilizers available, as N content tends to be quite high in comparison to other organic materials (Moore et al., 1995; Davis et al., 2002). For example, Davis et al. (2002) showed that total N of poultry manure in Colorado and the Midwest averages 0.25% and 0.36% N, respectively; analogous values were 0.20% and 0.17% N for beef manure, and 0.12% and 0.25% N for dairy manure.

The C:N ratio of compost and manure may be altered during transportation and storage, depending on whether the conditions are aerobic or anaerobic (Murwira et al., 1994). Manures with high NH_4^+–N content, such as poultry manure, maintain high levels of ammonia volatilization, which are purportedly between 9 and 44% (Nahm, 2005), displaying a strong inverse correlation between ammonia losses and C:N ratio (Murwira et al., 1994; Moore et al., 1995). Nitrogen losses through NH_4^+–N volatilization will increase C:N ratios and ultimately N availability, but these losses tend to be greatest under dry, windy climatic conditions which facilitate evaporation and volatilization (Moore et al., 1995).

Similarly, most studies corroborate that poultry manure contains high levels of inorganic N as ammonium (NH_4^+–N) prior to handling and storage (Davis et al. 2002; Moore et al. 1995; Chae and Tabatabai, 1986). For cattle manure, ammonium levels are generally lower than for poultry manure; however, these values depend on the feeding regimen and, more specifically, whether the animals are beef or dairy cattle. Research conducted by Burger and Venterea (2007) indicated that, while NH_4^+–N content of manure from beef cattle may be as low as 5 mg kg^{-1}, NH_4^+–N levels reported for dairy cows (64 mg kg^{-1}) were higher than those found for turkeys (50 mg kg^{-1}). Similarly, a study comparing N mineralization from various manures and composts by Gale et al. (2006) demonstrated NH_4^+–N levels ranging from 49.3 to 82.7 mg kg^{-1} for uncomposted broiler manure and 6.9 to 24.0 mg kg^{-1} for solid dairy manure. The same study corroborated lower quantities of solid dairy manure

NO_3^--N, ranging between <3 and 6 mg kg^{-1}, while NO_3^--N from broilers was between 223 and 56 mg kg^{-1}.

Handling, storage, and management of both compost and manure affect nutrient composition in other ways as well. For example, the quantity and type of bedding material in animal production systems alters the C:N ratios for stored manures, depending on the C:N ratio and chemical properties of the bedding. As discussed above, high C:N ratios for bedding will increase the C:N ratio when combined with raw manure, while materials high in lignin also engender nutrient immobilization (Seiter and Horwath, 2004).

Storage practices also directly impact organic amendment nutrient composition. Placement of roofing over stored organic materials prevents exposure to the elements; in particular, roofing mitigates N losses through NH_4^+–N volatilization due to high temperatures induced by solar radiation. Further, if organic materials are stored on a permeable surface, precipitation may exacerbate N leaching from the compost or manure pile (Lekasi et al., 2003; Seiter and Horwath, 2004).

The C:N ratio, total nitrogen and NH_4^+–N also can vary depending on feed, as increased quantities of total N, NH_4^+–N, and urine are positively correlated with increases in dry matter intake and dietary crude protein, but negatively correlated with dietary organic matter and protein digestibility, as well as optimization of essential amino acids in feed (Nahm, 2005; Klopfenstein et al., 2002; Nahm, 2007). Total quantity of manure produced tends to follow a similar pattern, with large quantities of dietary fiber linked to increases in excreta (Vu et al., 2009). Variability in feeds also has a differential impact on the partitioning of excreta between liquid (urine) and solid waste (feces), with dietary fiber demonstrating a positive correlation in excretion of feces as well as feces N content due to reduced N digestibility. By contrast, urine production is negatively correlated with dietary fiber, but positively correlated with increases in dietary N and protein level (Klopfenstein et al., 2002; Vu et al., 2009). The C:N ratio of manure is also correlated with increased dietary fiber intake (Vu et al., 2009).

Furthermore, while increased dietary N and protein content maintain a positive relationship with urine production, urinal N tends to come in the form of NH_4^+–N. Ammonium levels are generally higher in liquid than solid manures; thus, losses of N through volatilization and, under anaerobic conditions, denitrification, tend to be greater for liquid manure than solid (Burger and Venterea, 2007; Seiter and Horwath, 2004). Following surface application to land, ammonia losses through volatilization for poultry manure may be as high as 65% of the NH_4^+–N content and 35% of the NH_4^+–N + uric acid N content (Chambers et al., 1999; Seiter and Horwath, 2004). It should be noted, however, that application of amendments to highly acidic soils may be beneficial to crop growth early in the season, but subsequent nitrification of NH_4^+–N may exhibit deleterious effects due to release of acidifying H^+ ions (Chambers et al., 1999).

Cultural practices affecting nitrogen availability

The effects of cultural practices such as tillage and soil amendment incorporation on N mineralization and availability have been extensively reviewed in the literature (Brady and Weil, 1999; Pekrun et al., 2003; Seiter and Horwath, 2004). Tillage effects on soil fertility, N mineralization, and availability must be disaggregated between short-term and long-term impacts. Long-term effects of tillage tend to negatively impact SOM levels and, subsequently, the inherent capacity of SOM to provide N, depending on tillage type, intensity, and frequency. The higher the intensity and frequency of tillage, the greater the depletion of SOM. High intensity and frequency of tillage also lowers nutrient storage capacity and decreases rates of nutrient cycling, while also negatively impacting soil physical properties (Pekrun et al., 2003). Tilling of virgin land or land under untilled perennial vegetation generates a disequilibrium in the foregoing parameters until a new equilibrium condition is reached, wherein levels of SOM and associated factors controlling nutrient cycling become stabilized (Cambardella, 2010). Given their dependency on these processes for nutrition, the effect of tillage on soil microbial communities also tends to be negative (Sylvia et al., 2004).

However, the effects of tillage on N mineralization and availability are typically positive in the short-term. Tillage increases mineralization of both SOM and any incorporated plant residues or pre-applied soil amendments through mixing of these materials into the soil A_p horizon, facilitating better physical contact between the soil and organic materials. Similarly, tillage enhances mineralization through increased aeration of the soil and by breaking up large soil macroaggregates which are subsequently more accessible to soil microorganisms (Pekrun et al., 2003; Seiter and Horwath, 2004). Tillage also creates a more even distribution of organic materials and associated mineralizable nutrients with depth in the soil profile, with consequences for plant nutrient availability (Pekrun et al., 2003).

Incorporation of high ammonium soil amendments can also reduce gaseous losses of NH_4^+-N. However, as noted by Chambers et al. (1999), amendments must be incorporated very shortly after application in order for incorporation to effectively reduce volatilization losses.

Soil Amendment Use in Smallholder Farming Systems

Issues concerning feed quality and residue handling and storage are particularly salient to low-income smallholder agricultural systems prevalent in developing countries. For example, a study by Lekasi et al. (2003) in Central Kenya provided an overview of the prevailing manure management practices in smallholder systems and their impact on cattle manure quality. The study found a diverse range of roofing and drainage systems, as the majority of the farmers had at least partial roofing, but only 46% of farmers kept manure under some sort of shade and 90% did not cover manure. Similarly, despite 96% of farmers having soil floors, 56% of survey correspondents were classified as having poor drainage, leading to greater retention of urine in the storage area.

In the same study, manure was preferentially stored in piles or pits, rather than in a deep bedding system, although the majority of farmers (69%) used some sort of bedding material, with many adding various other organic materials, such as crop residues, to manure piles. The majority of farmers reported turning manure piles infrequently or not at all. Manure piles ranged in age from one to eight months, with five months being the most common. Further, the study found that the use of bedding tended to decrease inorganic N concentrations and increase C:N ratios, while turning the manure pile increased inorganic N concentrations and lowered C:N ratios. Farmers with poor drainage or those who added urine to manure piles did not have significantly different C:N ratios or N concentrations compared to respondents who did not employ such practices, indicating that urinary N is not efficiently conserved under the management practices common in these systems. Assuming cattle receive adequate hydration, urinary losses in such smallholder systems could be as high as 98 kg per year (Lekasi et al., 1998). Similarly, Powell et al. (1992, 1999) estimated that

40-60% of manure N is lost when livestock are kept using traditional management practices such as stall-feeding and extensive grazing and that corralling animals, accompanied by improved bedding materials, would dramatically reduce N losses (Saleem, 1998).

Problems associated with low quantity and quality of feed in smallholder agricultural systems have also received a fair amount of treatment in the literature (Ayatunde et al., 2005; Saleem, 1998). Broadly speaking, however, livestock nutritional problems are similar to those experienced by humans in developing countries, with low and declining crop productivity exacerbated by pest and disease problems (Steinfeld et al., 2006; Ayatunde et al., 2005). As the majority of agronomic and horticultural crops are reserved for human consumption, livestock diets in developing countries are dominated by forages and crop residues that may be inadequate in meeting animal energy and protein requirements (Ampaire and Rothschild, 2010; Saleem, 1998). The consequences of low feed quantity and quality were discussed in the previous paragraphs.

Given the foregoing discussion of heterogeneity of manure composition within and between farms, between regions, and even within piles, prediction of plant available nutrients from manure can be very difficult (Davis et al., 2002). While in the United States regional tables for predicting nutrient levels of various manures and organic wastes are available (Davis et al., 2002), such data is largely absent for African manures (Murwira et al., 1994). However, as discussed above, animal manures in Africa generally have comparatively lower quality than those for which data is readily available in the West (Murwira et al., 1994).

Phosphorus Effects on Plant Productivity

Although nitrogen is often considered the most limiting plant nutrient in agroecosystems, phosphorus (P) may also limit productivity in certain instances, particularly in the humid tropics (Brady and Weil, 1999; Sanchez, 1976). As detailed by Brady and Weil (1999), phosphorus represents a tripartite problem as far as its availability to plants is concerned: low total soil phosphorus content, unavailability of phosphorus to plants due to fixation and insolubility, and fixation of phosphorus added through soil amendments, crop residues, or fertilizers. Although not relevant to plant phosphorus availability in practical terms, total phosphorus (TP) in highly-weathered tropical soils, such as Oxisols and Ultisols, can be quite low and may be employed as a metric for gauging the extent of land degradation (Buresh et al., 1997; Sanchez, 1976).

Despite low levels of SOM, soil phosphorus stored in organic forms may account for between 60-80% of TP in highly-weathered soils such as Oxisols and Ultisols (Sanchez, 1976). Mineralization of P from SOM in these soils follows the same broad patterns discussed above for N. However, levels of inorganic P in soil solution, where it becomes available for uptake by plants in the form of phosphate anions (HPO_4^{-2}, $H_2PO_4^{-}$), tend to be quite low compared to other macronutrients and may be as low as 0.001 mg kg^{-1} in low fertility soils (Brady and Weil, 1999).

For example, available/extractable P was low overall in experiments detailed in subsequent chapters (Chapters 2-4). For the experiments at Kabanyolo in south-central Uganda (Chapter 3), P concentration was highest in the 0 to15 cm interval of the northeast quadrant with a value of 18.25 mg kg^{-1} P. The lowest P concentration recorded was 3.22 mg kg^{-1} in the 15 to 30 cm interval of the northwest quadrant. The average P content for all samples was 6.91 mg kg^{-1}. Such values for available P were comparable to those found in Chapter 2 among 33 farmers in the Kamuli District, where the mean was 8.57 mg kg^{-1} P (standard deviations of 0.05 and 6.14, respectively) for soils sampled to a depth of 15 cm.

Data on soils in the Kampala area at Kawanda and Bukalasa, tabulated by Jameson (1970), demonstrated comparable P levels, reporting values of 27 mg kg^{-1} P and 37 mg kg^{-1} P, respectively. Other studies with data on topsoils (0-15cm or 0-20cm) in Uganda, such as those by Esilaba et al. (2005), displayed similar P concentrations for other locations in Uganda. The aforementioned study reported values ranging from 1.9 mg kg^{-1} P to 4.6 mg kg^{-1} P in the Mayuge District in eastern Uganda, while those reported by Tumuhairwe et al. (2007) in the semi-arid Mubende District of western Uganda ranged from 3.02 mg kg^{-1} P to 9.42 mg kg^{-1} P, with a reported mean of 5.11 mg kg^{-1} P.

Quantity of inorganic soil P in soil solution of acid soils is closely related to solubility of phosphorus-bearing compounds, as well as pH and the presence of iron- and aluminum-oxides. In soils where pH is low and associated levels of iron- and aluminum-oxides are high, dissolved inorganic P, mineralized from SOM or amendments, reacts with dissolved Fe^{3+} and Al^{3+} ions to form highly insoluble phosphorus-containing compounds in a process known as phosphorus fixation or retention (Brady and Weil, 1999; Sanchez, 1976). However, most P fixation probably occurs when dissolved P becomes adsorbed to the foregoing Al- and Fe-oxides that occur on the interlayer and external surfaces of clay particles.

Although P fixed in this manner is merely held to anion exchange sites on particle surfaces and may therefore become gradually available to plants, inorganic iron- and aluminum-bound P compounds tend to become less soluble and increasingly unavailable to plants with time. The precipitation of further oxides onto the initial iron- and aluminum-bound phosphorus compounds frequently results in the “burial” of phosphate ions, which are subsequently occluded from contact with the soil solution and become highly unavailable to plants (Brady and Weil, 1999; Sanchez, 1976). The foregoing processes, particularly the latter, are responsible for low levels of plant available phosphorus in tropical soils. Thus, the focus of this thesis project revolved around the potential for application of manure and composted manure to supply additional N and P to enhance amaranth productivity, yield and protein content.

Thesis Organization

This thesis is organized into five chapters. Chapter 1 consists of a literature review and thesis organization. Chapter 2 represents the survey conducted of 34 farmers in the Kamuli District regarding their amaranth production practices, use of soil amendments and soil properties. Chapter 3 details three on-station experiments on the effect of soil amendments on amaranth productivity, yield and protein content. Chapter 4 examines these same parameters, but in the context of on-farm trials in the Kamuli District. Chapter 5 consists of conclusions and recommendations.

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CHAPTER TWO: SURVEY OF GRAIN AMARANTH PRODUCTION AND SOIL PROPERTIES IN KAMULI DISTRICT OF UGANDA

Introduction

A survey was conducted in June 2009 among smallholder farmers in the Kamuli District of eastern Uganda (Figure 1) to determine agronomic practices and issues associated with grain amaranth production, and develop a database of soil properties associated with amaranth fields. Grain amaranth has been present in eastern Uganda since at least 2005, when the Ugandan non-governmental organization (NGO), Volunteer Efforts for Development Concerns (VEDCO), began promoting the crop as a source of high quality non-animal protein among smallholder farmers. Much of VEDCO's promotional activity has been concentrated in the Kamuli District of eastern Uganda, in cooperation with Iowa State University's Center for Sustainable Rural Livelihoods (CSRL). However, relatively little was known about agronomic practices for grain amaranth among adoptive farmers. A survey of amaranth growers facilitated by VEDCO personnel was therefore initiated in June 2009 to discern general farming practices for amaranth among Kamuli farmers.

Materials and Methods

Survey characteristics

A total of 34 farmers were interviewed in three sub-counties of the Kamuli District between 13 and 18 June 2009. Interviews consisted of a questionnaire (Appendix I) on production practices and a sampling of soils that farmers deemed representative of amaranth growing areas on their particular farm. Inherent soil fertility was determined by sampling soil in the first 15 cm to analyze for soil nutrients, physical and chemical properties.

Interview respondents were selected through a non-probabilistic survey sampling method known as snowball or chain referral sampling (Snijders, 1992). Snowball sampling depends on referrals from initial respondents to generate further respondents and is often used when a sampling characteristic (such as production of grain amaranth) is rare and where the desired characteristic may be difficult or costly to find. Though snowball sampling may facilitate the location of appropriate respondents, this comes at the cost of introducing bias into the results, as the sample is unlikely to accurately represent the survey population as a whole. Nevertheless, snowball sampling is frequently used in qualitative sociological research (Biernacki and Waldorf, 1992).

The scope of the survey was confined to three sub-counties of Bugabula county in southwestern Kamuli District where the VEDCO/CSRL program operates (Figure 2) – Bugulumbya (47% of respondents), Butansi (35%), and Namasagali (18%). Survey respondents were selected from five parishes, including Butansi (15% of farmers), Kasambira (21%), Naluwoli (21%), Namasagali (18%), Nawanende (26%), as well as 15 villages. Sampling of respondents in these areas was facilitated by networking with VEDCO and their contacts trained as Rural Development Extensionists (RDEs) and/or Community Health and Nutrition Workers (CHNWs). Surveys were conducted by visiting respondents on their individual farm/homestead, with translation assistance provided by VEDCO–Kamuli office personnel, including Dorothy Masinde, Associate Director of Uganda Operations for CSRL, and Nutritionist Benon Musasizi.

Surveying began on 13 June 2009 with three farmers in Buganya and Bugabula counties. Surveying resumed on 15 June 2009, and was completed on 18 June 2009. The remaining 31 respondents were surveyed during this latter time period. The interview process generally lasted for one hour on average, with nearly all farm visits including an inspection of current or previous amaranth fields.

Soil sampling

Soil samples from each individual farmer's field were obtained following interviews by coring soils with a hand auger to a depth of 15 cm in a typical amaranth growing area and placing the individual farmer samples in separate plastic bags. After collection, soil samples were transferred to the Soil Science Laboratory at Makerere University in Kampala where they were air-dried for several days. Soils were then analyzed for pH, soil organic matter (SOM), total nitrogen (TN), available phosphorus (P), exchanges bases of sodium (Na), potassium (K), magnesium (Mg), and calcium (Ca), and texture using standard procedures described in Okalebo et al. (1993).

Individual fields for sampling were selected for each farmer based on association with grain amaranth. If an individual respondent was growing grain amaranth at the time of the survey, soil samples were obtained from the center of the amaranth field. However, since not all farmers were actively growing grain amaranth at the time of the visit, some soil samples were taken either from fields in which grain amaranth had been planted during the most recent growing season, or from fields where the farmer intended to plant the crop during the next growing season.

Three individual farm's soil samples were lost in transition due to labeling issues. However, two additional samples were obtained from farmers who were not involved in the original interview process, but who participated in the on-farm grain amaranth trials (Chapter 4). Inclusion of these farmers resulted in a total of 33 individual soil samples for the area.

Results and Discussion

Farm demographics

Survey respondents were classified based on demographic characteristics, such as age and gender, in addition to geographical information. Respondents included 23 women (72%), nine men, and two institutions (data not presented). The institutions interviewed were both primary schools, Kasambira Primary School and Naluwoli Primary School, both of which have school garden projects on their properties. Interviews at both institutions were conducted with senior administrators charged with overseeing the school garden projects. The average subject age was 43 with a standard deviation of 11 years. The minimum subject age was 30, while the maximum subject age was 75. Women respondents were 42 years old on average with a standard deviation of 9.1, while men were slightly older, with an average age of 46 and standard deviation of 15.1.

There are several reasons one might expect to find a high proportion of women to men in a survey of this nature. Although women's roles in African agriculture are fairly heterogeneous, gender division of labor in agriculture is ubiquitous, as women are responsible for cultivation, weeding, and harvesting. Similarly, the production of staple food crops for home consumption (i.e., grain amaranth) typically falls within the sphere of women's activities, while production of cash crops is often controlled by men (Ellis, 2000).

Asymmetric gender relations in rural Africa are the norm rather than the exception. As acknowledged by Butler and Mazur (2007), women's education and skill development tend to lag behind that of men, while, "Often women do not have access to the resources to increase productivity; their time is constrained by the need to manage multiple responsibilities, and they frequently lack information and affordable access to labor-saving technologies." Therefore, CSRL and VEDCO interventions, such as introduction of grain amaranth, actively target women as participants.

The relatively older age of survey respondents may be explained in part by the higher differential impact of HIV/AIDS on adults in the 25–34 year old age group. Although the estimated prevalence of HIV/AIDS in Uganda (5.4%) (WHO, 2008), is relatively low in Uganda compared to other African countries, this impact is felt more acutely in Uganda's rural communities, where it is the leading cause of death (Quinn, 1996). Sseguya et al. (2009) reported that 10% of the population across the entire community in Kamuli experienced health difficulties related to HIV/AIDS, nearly double the national average.

Amaranth field characteristics and crop rotations

The average area planted in amaranth for all respondents was 569 m^2 (6168 ft^2) with a standard deviation of 536 m^2 (5767 ft^2) (data not presented). The minimum area planted in amaranth was 19 m^2, while the maximum was 1858 m^2. Female respondents planted an average of 581 m^2 with a standard deviation of 552 m^2, while male respondents planted 557 m^2 on average, with a standard deviation of 526 m^2. The two primary schools planted 557 m^2 and 465 m^2 in amaranth. These values were lower than those reported in a 2007 VEDCO survey of 338 farmers in area, where the average area planted in grain amaranth was 1013 m^2 (10,895 ft^2, 0.25 acres) (Sseguya, 2007).

When respondents were asked to list the three most recent previous crops grown on the land on which grain amaranth was being cultivated or had been cultivated at the time of the survey, maize (*Zea mays* L.) was the mostly commonly grown crop prior to amaranth cultivation (data not presented). A total of 19 of the 34 respondents grew maize in at least one of the last three rotations. Fifteen respondents reported having grown dry beans (*Phaseolus vulgaris* L.), while another 10 grew potato (*Solanum tuberosum* L.). Also fairly common were matooke banana (*Musa* spp. L.), which seven respondents had grown, while nine reported growing cassava (*Manihot esculenta* Crantz). A variety of other crops were reported; however, none of these had been grown by more than three respondents. Such crops included cowpea (*Vigna unguiculata* L.), coffee (*Coffea robusta* L.), eggplant (*Solanum melongena* L.), groundnuts (*Arachis hypogaea* L.), greens (*Brassica oleracea* L.), nakati (*Solanum aethiopicum* L.), sorghum (*Sorghum bicolor* L.), soybeans (*Glycine max* L.*)*, and sweet potato (*Ipomoea batatas* L.). Two instances of fallowing prior to amaranth planting were also reported.

During the most recent growing season, maize was again the most commonly grown crop, with 13 of the 19 total maize plantings occurring during this time period. Similarly, dry beans and potato were both planted in six instances as the second most common crop in the last growing season. Other crops/fallow periods were mentioned but none of these were grown by more than two respondents: a fallow period (2), cassava (1), coffee (1), eggplant (1), matooke banana (1), nakati (1), greens (1), and sweet potato (1).

In the second most recent growing season, dry beans were the most commonly plant crop, with eight respondents reporting. Six respondents reported growing cassava, while five grew maize. Other crops included matooke banana (3), potato (3), cowpeas (1), eggplant (1), groundnuts (1), and sorghum (1).

Similar crops were grown in the third most recent growing season with respondents purportedly growing matooke banana (3), cassava (2), groundnuts (2), sweet potato (2), dry beans (1), greens (1), potato (1), and soybeans (1). Although the array of crops grown in

Kamuli is dynamic and changes from year to year, these numbers are in line with those reported in a 2007 VEDCO survey of 338 farmers in area. The report indicates that the suite of crops discussed above predominate in roughly the foregoing order, with 98.5% of survey respondents having grown maize, sweet potatoes (98.2%), cassava (95.3%), matooke banana (91.4%), dry beans (89.6), coffee (79.9%), and groundnuts (77.5%). Most of the other crops grown in amaranth fields during previous seasons were produced by less than 50% of VEDCO survey respondents.

Based on the foregoing survey, it appears that annual crops and some of the less common crops (grown by less than 50% of the population in the VEDCO survey) are overrepresented in the amaranth survey fields, while perennials like cassava and matooke banana tend to be less common. Probably this phenomenon is due simply to the ease with which annual crops may be rotated between growing seasons compared to perennials.

Weather conditions

When respondents were asked to state if the weather during last growing season was regular, irregular, or a mixture, the majority of respondents (24) indicated that the weather would best be described as a “mixture,” while six respondents reported that the weather had been regular during this time period (data not presented). Another four characterized the weather as irregular. Both informal and scientific studies corroborate a trend of increasing precipitation variability and lengthening of the dry season associated with ENSO phenomena for Kamuli and the Lake Victoria littoral area, more generally (Kizza et al., 2009; Phillips and McIntyre, 2000; Sseguya et al., 2009).

Amaranth cultivation practices

Amaranth variety selection. When respondents were asked which varieties of grain amaranth they were planting, given the option of “golden”, “cream” (white), or both, “golden” was by far the most common variety planted, with a total of 30 respondents reportedly growing the “golden” variety (data not presented). Of these, 19 respondents reported growing only the “golden” variety, while the other 11 claimed to have planted both “golden” and “cream” varieties. The “cream” variety was grown by a total of 15 respondents, of whom only four planted the “cream” variety exclusively, with the additional 11 reporting to have planted both “golden” and “cream” varieties.

A report by Nabakabya and Nakimbugwe (2007) on post-harvest handling and use of grain amaranth in Kamuli provides some insight as why “golden” tends to be more common than “cream” among amaranth farmers. The report indicated that farmers grew the “golden” variety due to purportedly higher nutritional content, while “cream” was grown for higher yields. The report also portends that farmers will tend to grow a particular variety if the seed is provisioned to them by VEDCO at reduced cost. Given that VEDCO and CSRL have focused on promotion of foods with increased nutritional density, it would make sense that the more nutritious “golden” variety would be promoted at the expense of “cream”, and thus more commonly produced by farmers. Similarly, markets for amaranth grain are relatively undeveloped, with only 36% of farmers reported to have sold amaranth grain in 2007 (VEDCO, 2007). Therefore, one might expect that farmers might prefer a more nutritious variety for household consumption over a higher yielding variety for sale.

Cropping patterns. Regarding the use of intercropping, respondents were queried as to whether they planted amaranth in pure stands, planted it with other crops, or both. Respondents selecting the latter two options were subsequently asked which other crops they plant with amaranth. The majority of the respondents (62%) indicated that they grew amaranth in pure stands, while 32% practiced intercropping (data not presented). One respondent stated that they planted both pure and intercropped stands; one individual gave no response to the question.

Respondents making use of intercropping were asked to list the other crops in the amaranth intercropping system. Most of the respondents indicated intercropping amaranth with matooke banana as the most common method used (6), as well as maize (4), sesame (*Sesamum indicum* L.) (2), cassava (2), and potato (1). Most of these responses included only one other crop grown in tandem with amaranth; however, two respondents reported double intercropping, while another utilized three intercrops. All three cases where more than one intercrop was planted included maize and one of two other intercrops–either cassava or sesame. The respondent who reported growing three additional crops did so with a mixture of maize, cassava, and potato.

Planting date. When respondents were queried as to whether they planted grain amaranth as seed or as transplants, responses were entirely uniform, as all respondents indicated the use of seeds as the means of planting (data not presented). Responses were more variable regarding the question of planting time; specifically, the survey inquired as to when grain amaranth was planted in relation to the beginning of the rains locally. All respondents planted amaranth following the beginning of the rains - the mean planting date was 8.3 days after the beginning of the rains, with a standard deviation of 10.6 days. The smallest time-lapse between the beginning of the rains and planting was one day, while the largest time-lapse was 42 days. One respondent did not provide an answer to the inquiry. Informal reports indicated that the long rains, generally occurring from March to June in the Kamuli District, had been late for the 2009 season and did not arrive in some parts of the district until mid-April.

Tillage practices. Continuing with questions on cultivation practices prior to or associated with planting, respondents were asked to provide a ‘yes’ or ‘no’ response as to whether the soil was tilled prior to planting and, if ‘yes’, what was the means of tillage employed. All respondents answered in the affirmative to the foregoing inquest. The means of tillage was nearly as uniform, since all but three respondents claimed to have used a hand-hoe exclusively. The remaining respondents utilized draft power in the form of an ox-driven plow; however, two of these respondents also reported employing a hand-hoe for tillage purposes.

Soil tillage practices are indicative of the agricultural practices in the Kamuli area, where farming is generally extensive in nature and farmers have limited resources for increasing productivity. A baseline report by Sseguya and Masinde (2005) on rural livelihoods in Kamuli revealed that ox-plows are a relatively new technological innovation and are typically provided as a for-hire service, rather than owned by the farmers themselves.

Thinning and consumption of amaranth leaves. On the topic of production practices during the growing season (e.g., after planting), respondents uniformly answered in the affirmative regarding whether amaranth plantings were thinned and/or eaten as vegetables during the seedling or vegetative growth phase. Universal consumption and thinning of amaranth plants during the seedling and amaranth growth phases was also unsurprising, given that vegetable amaranths (*Amaranthus* spp.), known locally as ‘dodo’, are grown as a vegetable crop in Kamuli, as well as in the tropics globally (NRC, 2006; Sseguya and Masinde, 2005). Although, there does seem to be some variation between grain amaranth varieties and *Amaranthus* spp. more broadly concerning suitability and quality of leaves for household consumption (Abili, pers. comm.).

Pest management practices. On the inquiry regarding the use of pesticides in amaranth production, all respondents answered in the negative (data not presented). When respondents were asked to rate pest pressure on grain amaranth plantings as low, medium, or high, the majority of respondents indicated that insect problems were relatively minimal, as 23 (67%) designated their insect pressure as “low.” Six (18%) respondents reported medium levels of insect pressure, while the remaining five (15%) selected the “high” response.

Responses on the question of weed problems were split more evenly between the three options. In this case, medium levels of weed pressure were the most commonly selected option (44%), while another ten (29%) cited low weed pressure. The nine remaining respondents (26%) indicated that weeds were a major problem.

An inquiry was also made regarding whether respondents experienced difficulty with birds, specifically, disturbance and consumption of amaranth seed heads. Most respondents (55%) claimed that birds did not pose a problem for them, while 12 respondents (35%) reported that birds were observed eating amaranth seed. At least two other respondents answered in the affirmative to the inquiry, but specified that amaranth grains were consumed by domestic poultry after seeds had dropped to the ground, which was not the same as "bird predation."

The non-existent use of pesticides was an expected response, given the low levels of pesticide use and lack of agricultural inputs more generally in Uganda. As discussed below, with the exception of weeds, which can be dealt with through mechanical means, pest pressure on grain amaranth is relatively low compared to other crops commonly grown in the area.

Harvest dates. When respondents estimated the time between amaranth planting and maturity (i.e., how many days between planting and harvest), the mean time reported to amaranth maturity was 67 days, with a standard deviation of 14 days. The minimum number of days to maturity was 30, while the maximum was 90 days. Two respondents reported ranges rather than singular estimates and these were 45–70 and 45–75 days. Two other respondents, provided responses of 45 and 65 days each, while the last failed to register a response. As discussed in Chapter 1, these values were fairly normal, according to the literature. The varieties in question would be considered to be either early (<60 days) or medium-maturing (70-90 days) according to the standards employed by Gupta et al. (1992).

Soil amendments

Respondents were asked to state whether any soil amendments were applied to their grain amaranth fields. A reply in the affirmative precipitated a series of further questions seeking more detailed information on amendment use, while a negative response yielded no further questions. The majority of respondents (65%) said they did not apply any soil amendments, while 11 (32%) gave a rejoinder in the affirmative and were subjected to further questions (data not presented).

Of the respondents who made use of soil amendments, all but one reported employing at least some cow manure as an amendment. Three of the respondents made use of cow dung in conjunction with other amendment types, which included composted leaves (2) and goat dung (1). The individual who did not apply cow dung used poultry litter. Age of soil amendments widely varied. The mean age of the residues added to amaranth fields was 56 days, with a standard deviation of 48 days. The maximum residue age was 180 days and the minimum was 14 days. Responses on whether the amendment residues were turned regularly varied as follows, from least to most intensive: no turning (3), turning by chickens (1), turning once per month (3), turning twice per month (1), turning once per week (3), and turning twice per week (1).

The respondents were also asked to answer questions on amendment use in relation to cultivation. Regarding the timing of amendment application relative to planting date, all respondents indicated that amendments were applied concurrently with planting of grain amaranth (e.g. on the same day). The quality of the amendments used was ranked on a scale of 1 to 5, with 5 designating the highest quality and 1 the lowest. Respondents generally deemed amendments to be of high quality, as all selected a value of 3 or higher on the amendment quality scale. The majority of respondents (63%) evaluated the amendments as a 4 on the scale, indicating fairly high quality. Three others (27%) felt the amendments they used were of average quality and rated them as a 3, while one individual considered 5 the most appropriate value on the quality scale.

The foregoing discussion on manure use must be situated in the wider context of the primarily low-input, extensive, and resource-limited farming systems of Kamuli District and eastern Uganda. As alluded to by Sseguya (2007), the problem of land degradation due to a complex of factors associated with “population pressure and poor land use practices, cultivation of fragile lands (swamps and forest areas), and bush burning and deforestation. Resulting from the situation is a downward spiral of productivity, land degradation and poverty”. Such negative assertions regarding land degradation narratives are corroborated empirically in the literature for both eastern Uganda and sub-Saharan Africa more generally (Esilaba et al., 2005; Smaling et al., 1997).

Associated with the aforementioned problems are those related to livestock production. In addition to being kept in relatively low numbers, livestock in Kamuli are subject to numerous problems, including pests, diseases and issues with pasture/feed (Sseguya, 2007; Ampaire and Rothschild, 2010). Such problems are fairly common for livestock production in developing countries and tropical areas more broadly (Steinfeld et al., 2006; Ayantunde et al., 2005).

Further, these issues in livestock production portend problems concerning manure quantity and quality. Manure quality in East Africa, as detailed by Lekasi et al. (2003), tends to be variable in quality depending on numerous exogenous factors. Such factors include the presence or absence of roofing and bedding, animal diet, and animal type. However, values for manure nutrients are generally lower than those found in the developed world, signifying lower quality, based on a survey of cattle manure quality among 300 smallholder farmers in central Kenya conducted by Lekasi et al. (2003). Inherent in the low nutrient levels is a high C:N ratios relative to those found in developed countries.

It appears, however, that the Kamuli farmers in this survey did regard the manure used on amaranth as being of fairly high quality. Given the subjective nature of the inquiry, however, it remains unclear whether this assessment represents an absolute or merely relative appraisal of amendment quality.

The use of cattle manure as the principal soil amendment applied to grain amaranth was somewhat surprising in light of low cattle numbers relative to other livestock (i.e., chickens and goats). The underlying rationale for this phenomenon is obscured by the various endogenous factors underlying farmers' decision-making processes. Regarding the foregoing issues, work conducted by Lekasi et al. (2003) in Central Kenya indicates that farmers have a strong capacity to detect variations in manure quality. The same study also found that farmers preferred goat and poultry manure to cattle manure for boosting crop productivity. Similarly, the comparatively high percentage of farmers making use of manure to enhance grain amaranth production may be attributable to CSRL/VEDCO interventions aimed at ameliorating land use practices and natural resource management.

Soils

Soils for all 33 individual farmers from whom samples were collected are tabulated in Tables 1-3. Table 4 displays statistical measures across all 33 farmers and includes information on means and standard deviations, as well as maximum and minimum values for all soil parameters.

Soils across all 33 farmers from whom soil samples were collected can be classified primarily as sandy clay loams and sandy loams, since soil fine earth fraction values were relatively high for sand and clay, but lower for silt. Mean sand content for all samples was

62% with a standard deviation of 9%; the maximum reported value for sand content was 78%, while the minimum was 34%. Mean clay content was 23% for all samples with a standard deviation of 7%; clay content ranged from a high of 44% to a low of 8%. Mean silt content for all samples was 15% with a standard deviation of 4%. The maximum recorded silt content was as 24%, while the minimum value was 4%.

These values were similar than those reported for soils of 60 farms in the Kamuli District associated with the Namulonge Bean Program, sampled to a depth of 20 cm, which also classified soils in area primarily as sand clay loams and clay loams (NARO, 2009). Mean values for the Namulonge survey were 52% sand, 34% clay and 14% silt, with respective standard deviations of 5%, 5%, and 4%.

Soils were moderately acidic, with an average pH of 5.5 with a standard deviation of 0.7 across all soil samples. The maximum pH value recorded was 7.2, while the minimum was 4.4. These values were lower than those reported for the Namulonge survey, which maintained a mean pH of 6.4 with a standard deviation of 0.3.

Soil organic matter (SOM) was fairly low among participating farms, with a mean value of 2.46% across all samples. Standard deviation for SOM was 0.88 while the maximum and minimum values recorded were 4.12% SOM and 0.85% SOM, respectively. Soil nitrogen was measured as Total Nitrogen (TN) and maintained a mean of 0.13% N with a standard deviation of 0.03% across all samples. The highest TN value was recorded as 0.22% N, while the lowest value was 0.04% N.

Values for SOM were lower compared to the Namulonge Bean Program data, where the mean across 60 farms was 3.2% SOM with a standard deviation of 0.4%. The mean value for nitrogen in the Namulonge survey was also higher at 0.19% N with a standard deviation was 0.02%.

Mean phosphorus values were low overall, averaging 8.57 mg kg^{-1} P with a standard deviation of 6.14 mg kg^{-1} P. The maximum value for soil P was 38.08 mg kg^{-1} P, while the minimum was 5.57 mg kg^{-1} P. The Namulonge report attained lower soil P numbers than those demonstrated here, as 56 of 60 surveyed farms had soil P values below the minimum reporting standard of 5 mg kg^{-1} P.

Values for the four major soil cations, potassium, sodium, calcium, and magnesium, were also low. Potassium ranged from a maximum of 2.72 $Cmoles_c$ kg^{-1} K to a minimum of 0.36 $Cmoles_c$ kg^{-1} K, with a mean and standard deviation for all samples of 0.92 $Cmoles_c$ kg^{-1} K and 0.71 $Cmoles_c$ kg^{-1} K, respectively. Sodium ranged from a maximum of 0.13 $Cmoles_c$ kg^{-1} Na to a minimum 0.06 $Cmoles_c$ kg^{-1} Na; the mean sodium value for samples was 0.09 $Cmoles_c$ kg^{-1} Na with a standard deviation of 0.02 $Cmoles_c$ kg^{-1} Na. Calcium values ranged from a high of 8.2 $Cmoles_c$ kg^{-1} Ca to a low of 2.5 $Cmoles_c$ kg^{-1} Ca; the mean calcium value for all samples was 4.3 $Cmoles_c$ kg^{-1} Ca with a standard deviation of. The highest recorded value for magnesium was 2.94 $Cmoles_c$ kg^{-1} Mg, while the lowest 0.00 $Cmoles_c$ kg^{-1} Mg. The mean recorded magnesium value was 1.73 $Cmoles_c$ kg^{-1} Mg with a standard deviation of 0.64 $Cmoles_c$ kg^{-1} Mg. Tabulating the foregoing cation values provides approximate maximum of exchangeable bases at 11.88 $Cmoles_c$ kg^{-1} and minimum of 4.66 $Cmoles_c$ kg^{-1}. Mean exchangeable bases for all samples was 7.97 $Cmoles_c$ kg^{-1} with a standard deviation of 2.01 $Cmoles_c$ kg^{-1}.

Soil cation values for farms in the amaranth survey were generally lower than those found in the Namulonge survey (although values for sodium were not included in the latter), which reported mean values of 1.14 $Cmoles_c\ kg^{-1}$ K, 7.29 $Cmoles_c\ kg^{-1}$ Ca, and 4.13 $Cmoles_c\ kg^{-1}$ Mg, with respective standard deviations of 0.57 $Cmoles_c\ kg^{-1}$ K, 2.42 $Cmoles_c\ kg^{-1}$ Ca, and 0.79 $Cmoles_c\ kg^{-1}$ Mg.

The foregoing values indicate the possibility of systemic differences related to soil sampling. Indeed, of the nine individual farmers who were sampled in both the Namulonge survey and the amaranth survey, the trends cited above hold, with values for pH, SOM, and N all higher for same farms in the Namulonge report, while values for phosphorus and major soil cations were nearly identical. Soil physical properties for overlapping farms displayed an increase in sand content at the expense of clay for the amaranth survey results over the Namulonge survey, with values for silt content remaining equal.

Given that soil sampling depth differed between the two surveys, sampling depth may represent one factor responsible for above divergence, as the Namulonge samples were obtained to a depth 20 cm, while amaranth survey samples were taken to 15 cm. Although this may appear to represent the obvious explanation, the foregoing differences are the opposite of what one might expect, as both soil organic matter and nitrogen content tend to decrease with depth in the soil profile, while the trend for pH depends on soil type and sampling depth (Sanchez, 1976). Differences in soil physical and chemical properties, especially pH and aluminum levels, exert similar effects on soil P and the major cations.

Given the equivocal evidence of differences due to sampling depth, differences in analytical methodologies between laboratories could provide a possible resolution to the issue. Indeed, data gleaned from the mutually-sampled farmers may indicate that the two laboratories applied analytical techniques that were similar for phosphorus and soil cations (where numbers were nearly identical), but different for all other parameters.

Furthermore, the question of variation between fields on the land of individual farmers ought to be considered. Farmers may select fields with different characteristics for growing dry beans (fields for which were sampled in the Namulonge survey), as opposed to grain amaranth. Given that dry beans are an important staple in the area, grown by ~90% of all farmers, it does not seem unreasonable to speculate that farmers might allocate fields with more desirable physical and chemical properties to dry bean production than those planted to amaranth.

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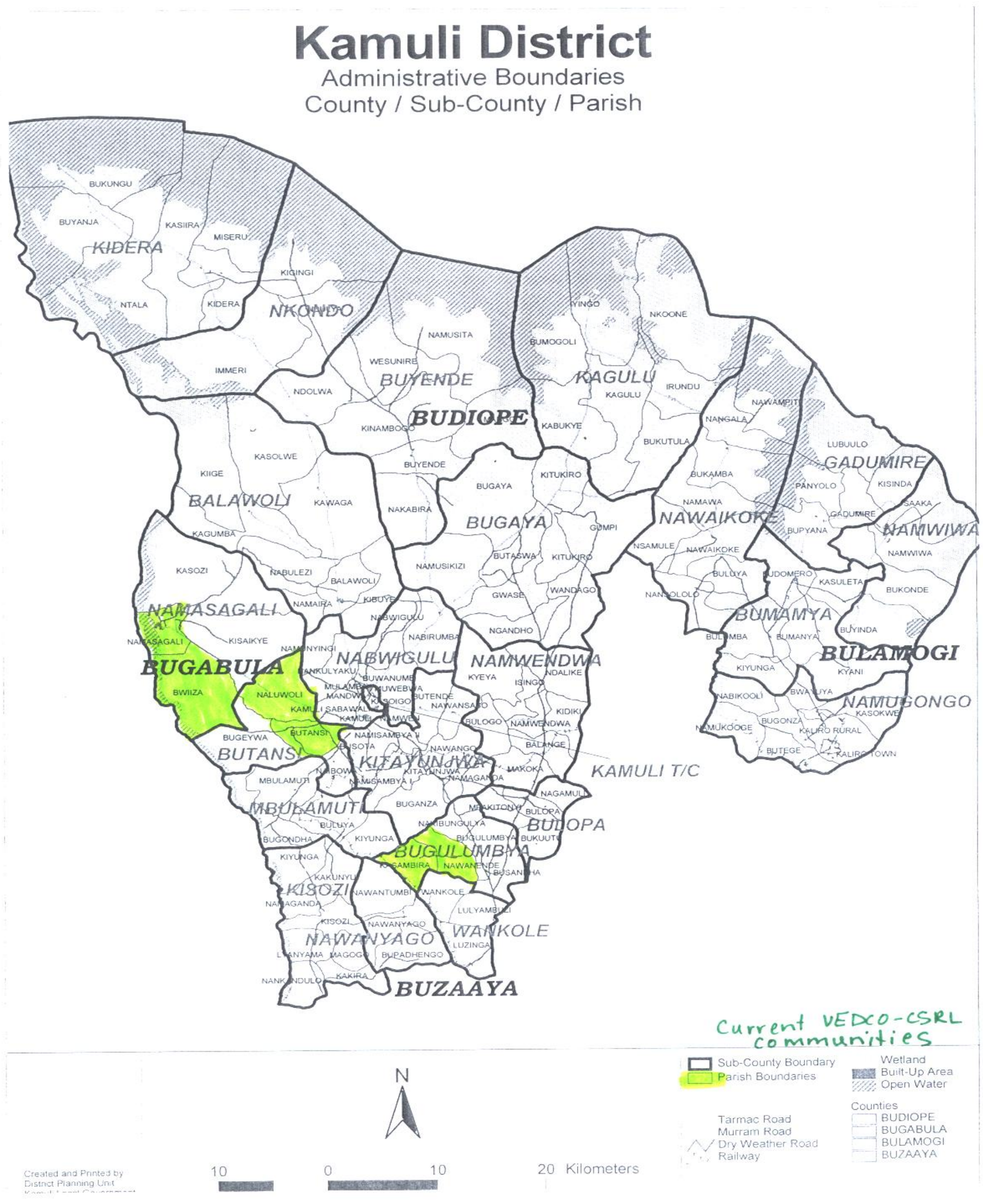
Figure 1. Map of Uganda with area of current CSRL/VEDCO communities circled.

Figure 2. Map of Kamuli District in eastern Uganda with current VEDCO/CSRL communities highlighted.



(Iowa State University (CSRL), 2008)

Table 1. Physical and chemical properties for upper 15 cm of soil from surveyed farms (1-11) in Kamuli District, Uganda.

Farm No.	Sub-county	Parish	pH	SOM (%)	N (%)	P	K	Na	Ca	Mg	Ex. bases[1]	Sand	Clay	Silt
						mg kg^{-1}	--------------------Cmoles$_c$ kg^{-1}--------------------					------------%----------		
1	Butansi	Butansi	4.4	1.89	0.10	4.91	0.68	0.09	6.1	2.80	9.7	68	22	10
2	Bugulumbya	Nawanende	5.5	2.49	0.08	9.66	0.51	0.13	6.7	1.90	9.2	64	24	12
3	Bugulumbya	Kasambira	6.4	2.12	0.09	5.57	1.86	0.09	3.4	1.84	7.2	64	20	16
4	Bugulumbya	Kasambira	4.8	1.97	0.10	6.10	0.27	0.07	3.1	1.77	5.2	60	22	18
5	Butansi	Butansi	5.8	2.71	0.11	5.76	1.08	0.08	2.5	1.00	4.7	62	24	14
6	Butansi	Naluwoli	7.2	1.00	0.09	9.55	2.41	0.08	6.8	1.94	11.2	78	8	14
7	Bugulumbya	Nawanende	5.4	3.46	0.19	38.80	1.62	0.08	3.5	1.00	6.2	52	30	18
8	Butansi	Butansi	5.2	3.68	0.20	7.16	0.63	0.11	5.2	1.80	7.7	64	24	12
9	Bugulumbya	Nawanende	5.4	3.08	0.12	7.33	0.33	0.12	6.8	2.46	9.7	60	22	18
10	Namasagali	Namasagali	5.8	2.19	0.14	4.77	0.72	0.08	3.1	0.89	4.8	34	44	22
11	Butansi	Butansi	5.8	3.20	0.20	7.39	0.40	0.08	3.6	1.38	5.5	60	24	16

[1] Exchangeable bases used as cation exchange capacity fails to account for H+ occupying exchange sites.

Table 2. Physical and chemical properties for upper 15 cm of soil from surveyed farms (12-22) in Kamuli District, Uganda.

Farm No.	Sub-county	Parish	pH	SOM (%)	N (%)	P	K	Na	Ca	Mg	Ex. bases[1]	Sand	Clay	Silt
						mg kg^{-1}	-------------------Cmoles$_c$ kg $^{-1}$-------------------					------------%----------		
12	Namasagali	Kasozi	5.5	2.17	0.11	8.47	0.57	0.07	5.5	1.35	7.5	60	28	12
13	Bugulumbya	Nawanende	5.5	1.82	0.10	8.54	0.94	0.13	6.8	1.84	9.7	50	34	16
14	Bugulumbya	Kasambira	4.4	1.08	0.09	18.81	0.60	0.08	4.6	0.00	5.3	62	26	12
15	Bugulumbya	Kasambira	5.5	2.04	0.14	7.21	0.44	0.07	4.6	0.87	6.0	64	20	16
16	Butansi	Naluwoli	5.1	0.85	0.05	5.35	0.79	0.08	5.6	1.84	8.3	72	14	14
17	Butansi	Naluwoli	4.9	4.12	0.22	13.27	0.41	0.08	6.5	2.88	9.9	58	24	18
18	Butansi	Naluwoli	6.0	1.65	0.12	7.23	0.80	0.07	4.5	1.35	6.7	68	24	8
19	Bugulumbya	Nawanende	6.5	3.98	0.20	4.91	1.12	0.11	6.5	2.66	10.4	62	28	10
20			7.2	2.86	0.10	8.17	2.69	0.13	6.1	1.86	10.8	76	12	12
21	Namasagali	Namasagali	5.5	3.16	0.20	6.31	1.99	0.07	5.3	1.94	9.3	44	34	22
22	Bugulumbya	Nawanende	5.1	2.12	0.10	8.22	0.13	0.11	4.7	1.78	6.7	62	22	16

[1] Exchangeable bases used as cation exchange capacity fails to account for H+ occupying exchange sites.

Table 3. Physical and chemical properties for upper 15 cm of soil from surveyed farms (23-33) in Kamuli District, Uganda.

Farm No.	Sub-county	Parish	pH	SOM (%)	N (%)	P	K	Na	Ca	Mg	Ex. bases[1]	Sand	Clay	Silt
						mg kg^{-1}	-------------------Cmoles$_c$ kg^{-1}------------------					------------%----------		
23	Bugulumbya	Kasambira	5.0	3.01	0.16	6.24	0.21	0.09	6.5	2.17	9.0	56	20	24
24	Butansi	Naluwoli	6.4	2.68	0.18	8.59	0.98	0.06	4.8	1.31	7.2	60	22	18
25	Butansi	Naluwoli	6.4	2.68	0.18	8.59	0.98	0.06	4.8	1.31	7.2	60	22	18
26	Bugulumbya	Nawanende	4.9	2.41	0.11	7.06	2.72	0.09	4.6	1.79	9.2	66	22	12
27	Bugulumbya	Nawanende	5.4	4.12	0.20	7.91	0.63	0.11	8.2	2.94	11.9	64	22	14
28	Bugulumbya	Kasambira	4.8	2.79	0.10	7.85	0.38	0.08	6.7	1.94	9.1	56	32	12
29	Namasagali	Namasagali	6.4	0.93	0.04	8.26	1.27	0.11	6.5	1.89	9.8	76	12	12
30	Namasagali	Namasagali	5.6	1.89	0.10	6.58	0.36	0.07	4.0	1.70	6.1	60	18	22
31	Bugulumbya	Kasambira	5.0	2.27	0.12	6.21	0.36	0.07	5.2	1.74	7.4	64	24	12
32	Butansi	Butansi	5.5	2.37	0.16	6.47	0.40	0.08	3.6	1.38	5.5	72	18	10
33	Butansi	Naluwoli	6.0	3.23	0.10	4.46	0.60	0.12	4.3	0.90	5.9	68	22	10

[1] Exchangeable bases used as cation exchange capacity fails to account for H+ occupying exchange sites.

Table 4. Statistical measures of physical and chemical properties for upper 15 cm of soil across all surveyed farmers in Kamuli District, Uganda.

Statistical measure	pH	SOM (%)	N (%)	P	K	Na	Ca	Mg	Ex. bases[1]	Sand	Clay	Silt
				mg kg^{-1}	--------------------Cmoles$_c$ kg^{-1}---------------------					------------%----------		
Mean	5.55	2.46	0.13	8.57	0.92	0.09	5.2	1.73	8.0	62	23	15
Standard deviation	0.71	0.88	0.04	6.14	0.71	0.02	1.4	0.64	2.0	9	7	4
Maximum	7.2	4.12	0.22	38.8	2.72	0.13	8.2	2.94	11.9	78	44	24
Minimum	4.4	0.85	0.04	4.46	0.13	0.06	2.5	0.00	4.7	34	8	8

[1] Exchangeable bases used as cation exchange capacity fails to account for H+ occupying exchange sites.

CHAPTER 3: ORGANIC GRAIN AMARANTH ON-STATION EXPERIMENTS IN UGANDA

Introduction: Project Overview

The following narrative documents the process involved in establishing and executing all aspects of my thesis research, including financial, personal and professional duties, in order to assist future students interested in working in Africa. In addition to the requirements for establishing and maintaining research plots, which constitutes a typical M.S. program, conducting thesis research in Uganda involved multiple logistical issues, which are described in the following sections.

Funding for travel and research

Initially, the proposed Ugandan amaranth project was encouraged by the Center for Sustainable Rural Livelihoods (CSRL-Iowa State University) that supported the research in concept but could not provide funding for the project. Financial support was provided in the form of a graduate student research assistantship by the Graduate Program in Sustainable Agriculture (GPSA) for the 2008-2009 academic year, while second-year financial support (2009-2010) was provided by GPSA (1/4-time) and a USDA-Sustainable Agriculture Research and Education (SARE) grant to improve soil quality in organic systems (1/4-time). Planning for the amaranth project began in late August 2008, when travel funds were secured through a combination of contributions from various sources within Iowa State University, including the Wallace Chair for Sustainable Agriculture, the Global Agriculture Program, and the Department of Horticulture.

This project would not have been possible without strong support from CSRL staff and Ugandan colleagues. Accommodations and agricultural research activities were coordinated with personnel from the Makerere University Faculty of Agriculture where Moses Tenywa, Professor of Soil Science, and Dorothy Nakimbugwe, Senior Lecturer in Food Science and Technology, were instrumental in the planning process. Dorothy Masinde, CSRL's Associate Director for Uganda Operations, and of staff of VEDCO (Volunteer Efforts for Development Concerns) helped coordinate my stay in Kamuli , the farmer survey, and the on-farm amaranth research. Richard Miiro, Haroon Sseguya and Ben Obaa – all Ph. D students at Iowa State University and faculty members at Makerere University aided in logistical arrangements in Uganda.

Air travel to Uganda consisted of twenty hours of flight time and a time change of eight hours; departure was on 13 May 2009 and arrival in Entebbe, Uganda, on the morning of 15 May 2009. From 15 to 20 May, I attended an IFOAM (International Federation of Organic Agriculture Movements) Training Workshop and the First African Organic Conference while staying at the Makerere University Guesthouse on the main campus in north-central Kampala.

The conference focused on a broad range of topics related to organic agriculture under the heading of "Fast tracking sustainable development in Africa through harnessing Organic Agriculture and Biotechnology." The conference prominently featured major organizations from the international development and organic agriculture arena, including ISOFAR (International Society of Organic Agricultural Research), ICROFS (International Centre for Research in Organic Food Systems), the United Nations Environment Programme, Agro-Eco Louis Bolk, IFOAM, and hosts Uganda Martyrs University (UMU) and the National Organic Agriculture Movement of Uganda (NOGAMU).

It became clear early in the conference proceedings that Uganda was indeed the logical location for a first official African Organic conference, as Uganda has more certified Organic farmers than any other African nation (over 200,000), while NOGAMU has been in existence for more than a decade. By comparison, most of the other countries represented at the conference maintained relatively new organizations founded with the last five years. Furthermore, East Africa seems to be far ahead of the rest of the continent south of the Sahara concerning development of the organic sector, as West and Southern Africa had few national representatives (notably Nigeria, Ghana, and Zambia).

During this time period, I also met with Moses Tenywa to discuss research plans and my forthcoming stay at the Makerere University Agricultural Research Institute (MUARIK) at Kabanyolo. On the first day of my arrival, after securing an essential low-cost mobile phone and drinking water for my stay, I accompanied Haroon to his land-holding in Luwero District, north of Kampala, which had a diversified, extensive agroecosystem in the Lake Victoria littoral zone in Uganda. This trip provided an introduction to smallholder agriculture, typical of the region.

For the majority of my stay (20 May 2009 – 17 August 2009), I was housed at the Continuing Agricultural Education Center (CAEC) within the MUARIK complex. MUARIK is a Makerere University owned and operated working and experimental research farm of 243 hectares (600 acres) located approximately 18 km north of Kampala in the Wakiso District of south-central Uganda. MUARIK is reached by travelling north on the Gayaza-Ziroobwe Road and turning east onto an unimproved dirt road just after Gayaza Town. The land comprising MUARIK is characteristic of the Lake Victoria region in south-central Uganda, with a topography distinguished by gently undulating hills.

The MUARIK territory houses numerous experiments for nearly all regionally important crop and livestock systems, particularly cooking banana (matooke) (*Musa* spp.) and robusta coffee (*Coffea canephora*). As of 2009, other research crops included soybeans (*Glycine max*) cotton (*Gossypium spp.),* and avocado (*Persea americana).* In addition to crop systems, animal agricultural research also represents an important component at MUARIK and includes experiments on cattle and pasture systems, poultry, pigs, goats, an apiary, and aquaculture.

The premises at MUARIK are also home to numerous employees and students from Makerere University and its affiliated institutions. Employees include carpenters, mechanics, and various agricultural technicians who typically live in or in close proximity to the MUARIK facilities. Undergraduate students in the Faculty of Agriculture at Makerere University are required to spend two extended stays at MUARIK in order to earn their degree–once for three months when courses are not in session between June and August of their freshman year (such students are described as “first years” by their peers) and again for an entire school year during their third year. These students generally stay in on-site dormitories. During my stay, other residents included students from a number of African countries working on post-graduate degrees through a regional program in Plant Breeding. People from villages and schools adjacent to the MUARIK property are also regular visitors, especially for water supplied at various outlets.

In addition to research experiments, many MUARIK employees maintain their own gardens, and plant food crops at the outer edges of experimental plots. Makerere University undergraduate students residing on-site are allotted a small portion of land at MUARIK on which they are permitted to plant food crops for personal use. As a result, the MUARIK landscape is dotted with a wide variety of local staples in addition to research crops, particularly cassava (*Manihot esculenta*), maize (*Zea mays*) and fruit trees such as jackfruit (*Artocarpus heterophyllus)*, mango (*Mangifera indica*), and papaya (*Carica papaya*).

Within MUARIK, I was housed at the Continuing Agricultural Education Center, which regularly hosts conferences and workshops on topics related to agricultural education and is one of eight departments within the Faculty of Agriculture at Makerere University. Founded in 1993 as a joint project with the World Bank and Government of Uganda under the Agricultural Research and Training Project (ARTP) through the National Agricultural Research Organization (NARO), CAEC has two dormitories for housing conference attendees, an office, a conference room, and a dining hall. A computer laboratory attached to the undergraduate student housing adjacent to the main CAEC facilities serves as a point for Internet access. I was housed in one of the two residential units and was provided with daily meals from the CAEC kitchen attached to a dining hall where meals were served.

During my stay at CAEC, I had daily interactions with the cooking and maintenance staff, as well as with the CAEC Coordinator, Fred Kawuzi, and other administrative personnel. Other personnel at MUARIK with whom I had regular interaction included MUARIK Secretary Fred Kasiko, who served as a money-holder during my first few weeks in Uganda until access to my account with the ATMs through large international banks began functioning consistently. I also had occasional interaction with the Farm Manager, Francis Nimukunda, who ranks second in administrative stature behind the Director at MUARIK, as well as the Assistant Farm Managers, Chrys Tweyambe and John Tumwijukye. Dr. Tenywa typically visited MUARIK at least once per week during my stay, which provided an opportunity to discuss the progression of my research project.

As the grain amaranth experiment got under way during the first weeks of my stay, I relied on Staff Carpenter Charles Aziz and Staff Mechanic Richard Okello for daily critical assistance in the process of establishing experimental plots on-site. Similarly, two fourth-year undergraduate candidates for a Bachelor of Science in Agriculture at Makerere University, Alex Abili and Geofrey Gabiri, were assigned to cooperate with me on the project by Professors Dorothy Nakimbugwe (Food Science) and Moses Tenywa, respectively. Makerere University requires candidates for a B.S. in Agriculture to conduct a research project at some point during their fourth-year; in this instance, both Mr. Gabiri and Mr. Abili fully integrated their research projects into my own, to the benefit of all parties involved.

Like many degrees, the B.S. in Agriculture at Makerere affords students the opportunity to develop a field of emphasis and students are generally encouraged to use the aforementioned research project to sharpen their expertise in an area of their choosing. Alex Abili chose to focus on Crop Science and his project coincided with my own, as he also is evaluating the effects of organic soil amendments on grain amaranth yields. Geofrey Gabiri has Soil Science as an area of emphasis and developed a research project on evapotranspiration, utilizing my study for measuring water loss from plants and soils. Mr. Gabiri’s project facilitated collection of critical information such as temperature, precipitation, and soil moisture. The latter was measured on a regular basis by Mr. Gabiri using a time-domain reflectometer (TDR), as well as tensiometers.

The importance of organic soil amendments, such as compost and manure, as well as soil data to the experimental design entailed participation by Francis Ogwang, M.S. in Soil Science, under the guidance of Dr. Tenywa, and Bonny Balikuddembe, Senior Laboratory Technologist at Makerere University Soil Science Laboratory. Francis Ogwang is principally researching compost and, more generally, soil amendments and is charged with maintaining demonstration compost bins at MUARIK. Mr. Ogwang was instrumental in assisting me in obtaining compost and manure for experimental use. Mr. Balikuddembe conducted all soils analyses, which cost approximately 10,000 USh (slightly less than $5 USD) per sample for the full suite of soil physical and chemical properties, including pH, organic matter, nitrogen, available phosphorus, potassium, calcium, magnesium, sodium, and the fine earth fraction (amount of sand, silt and clay).

Travel and transport within Uganda

There are three modes of public transportation that are widely available throughout Uganda: ‘boda-boda’ (motorcycle), ‘share taxi’ (sometimes referred to as “matatus” locally), and “special hire” taxis (private taxi). I made use of the former two options on a regular basis, as these are a significantly more cost-effective means of transport than special hire. However, special hires are useful and necessary when travelling with a large amount of luggage and I utilized these for airport transport, as well as moving between my initial quarters at the Makerere University Guesthouse and MUARIK.

Conveyance between MUARIK and Kampala is usually relatively straightforward and was a voyage I made fairly regularly to make use of facilities at the Makerere University main campus in Kampala. Direct travel to MUARIK by share taxi is typically impractical, as taxis travelling past Gayaza Town are few in number. The best option for reaching MUARIK, therefore, involved finding a boda-boda in Gayaza Town and negotiating a fee for transport. While boda-bodas are typically easy to locate in Gayaza Town, finding a boda-boda from MUARIK to Gayaza is somewhat more complicated, requiring that one walk a few hundred meters to Gayaza Road from the MUARIK property and flag down southbound boda-boda. Boda-boda fees for this particular route averaged about 600 Ugandan shillings (USh), or 25 cents USD as of August 2009.

From Gayaza Town, one may then board a share taxi travelling south on Gayaza Road to one of two taxi parks in central Kampala. Share taxis are an inexpensive but often cramped and uncomfortable means of transportation that offer transit between numerous locations throughout Uganda. Share taxis are almost invariably large vans capable of seating up to 14 passengers; individual vans are registered as taxis with the Ugandan government and are marked with an insignia to designate this capacity. Aside from registration requirements, share taxis operate on a rather informal basis with definite stops only at the van's final destination; all intermittent stops are at the request of the passenger. The vans are not marked according to destination and instead rely on vocalizations from the van's conductor to indicate the destination to would-be passengers. The share taxi system invariably consists of two men in each van, a driver and a conductor; the latter is charged with coordinating the pick-up, drop off, and collecting of fees from passengers.

Share taxi transit between Gayaza and Kampala costs 2000 USh or approximately $1 USD as of late 2009 and involves a journey of 45 to 90 minutes depending on traffic and the whims of the van operators and passengers. When travelling to Makerere University from Gayaza, I would disembark, prior to reaching the downtown Kampala taxi park, at central junction called Wandegaya and then make the short walk up Makerere Hill to reach the main campus. When I wanted to travel to downtown Kampala, which occurred on a regular basis, I would continue travelling on the downtown-bound share taxi and disembark at the desired location. I frequented the downtown area to make necessary financial transactions, eat, or make purchases, as the area boasts a concentration of banks, foreign exchange bureaus, stores, and restaurants.

A number of Western-style malls have been built in central Kampala during the past decade or so, and these offer Uganda's highest concentration of products typical of the modern developed world. Essential items, such as bottled water, can be purchased at outlets housed within the malls. Though they can be reached on-foot, none of major malls are located in the downtown area and a boda-boda or special hire is needed to reach these locations directly.

The two taxi parks in downtown Kampala form a national hub of public transportation in Uganda and direct connections can be made to most any large town in the country from one of the two parks. For my trips to Kamuli, the site of the on-farm trials, share taxis were utilized from the new taxi park to Kamuli Town at a cost of about 7000 USh ($3.50 USD) for a trip of three to four hours. VEDCO headquarters, the student guesthouse, and Hotel Pentagon are all within walking distance of Kamuli Town taxi park. The previous transport descriptions underscore the difficulty of efficient travel between research sites.

Experimental site description at MUARIK

After arrival at MUARIK facilities on 21 May 2009, a site was selected for research on a gently sloping east-west hillside (slope of approximately 11%) in the northeast corner of the property at 0°28'6.3"N latitude and 32°36'46.5"E longitude. The site had previously been planted with matooke bananas for at least ten years and was thick with bananas and weedy understory vegetation. The site had been in disuse for some time and many banana plants had succumbed to pests, especially black and yellow sigatoka (*Mycosphaerella* spp.), but also infestation by banana weevil (*Cosmopolites sordidus*) and nemtatodes. Site microtopography was heterogeneous, with multiple potholes and gullies.

The banana plots were accessible by a road to the west, flanked by coffee plantings to the south, and separated by a fence from an avocado grove and apiary to the east. To the southeast by some 80 m was an experimental unit for poultry and a small cattle stall, while due east about 85 m in the trough of a hill was an artificial pond used for aquaculture experimentation. Since the experiment was scheduled for the dry season, it was determined that irrigation would be required and, to facilitate this end, the site was initially selected because of its proximity to the pond.

Materials and Methods

Experiment 1: On-Station Dry Season Amaranth Production

Field preparation. Field preparation consisted of 40 hours from 26 to 30 May, beginning with the clearing of aboveground banana pseudostems from an area of 40 m by 35 m within the original matooke banana experiment; pseudostems were cleared from the road in the west to the avocado grove in the east (35 m), while removing all pseudostems for 40 m to the north of the coffee plants. The cleared area was then disked using a Baldan Graxa Semi-Mount, which was well-used and rusted. After completion of disking, mechanical field preparation continued with the cleared area twice subjected to harrowing. After the foregoing mechanical field preparation, numerous large soil aggregates remained on the site, along with banana corms, and it was determined that further field preparation would be required in order to fashion an appropriate seed bed for grain amaranth.

An area of 36 x 12m within the 40 x 35m cleared area was designated for use as experimental plots. Subsequently, this area was manually cleared of visible remaining banana corms. Plots were then irrigated manually by collecting water in 20 L plastic cans from a hose at the poultry unit and transferring collected water to 8 L watering cans. Watering cans were then used to directly irrigate the plots, dispensing approximately 8L of water per 4 m^2. Special attention was paid to saturating large soil aggregates with water in order to facilitate breaking up clods. Following manual irrigation, three additional laborers were hired at a sum of 30,000 USh to break up large soil aggregates and level out site microtopography using hand hoes. A rain event occurred immediately after completion of field preparation activities, which facilitated seedbed preparation. Attempts made to establish a mechanical irrigation system on 4 June were circumvented by faulty equipment and insufficient water volume to reach all plots evenly. Plots were therefore irrigated manually from this time forward.

Experimental design. Due to the possibility of intra-site variation in soil properties, particularly with the east-west slope, a Latin Square design was selected to control variation related to rows and columns in the field. The Latin Square design involves the random assignment of each treatment in rows and columns, with each treatment appearing in each row and each column exactly once. For the design to function there must be an equal number of treatments, rows, and columns.

Two sets of treatments were employed in all experiments conducted at MUARIK. The main treatment set was varieties of grain amaranth: “cream”, “golden” and ‘Plainsman’. For the Experiment 1, the “cream” and “golden” amaranth were unnamed varieties collected and saved from Dr. Nakimbugwe’s lab, while ‘Plainsman’ seeds were derived from Dr. Nakimbugwe’s lab via Ohio State University. Experiment 2 and Experiment 3 used seed harvested from amaranth plants grown in Experiment 1 as planting material. The Latin

Square design was blocked by variety, with each variety occurring once in each row and once in each column (Figure 1). Treatment blocks measured 42 m^2 (14 x 3m) and were numbered from one to nine, beginning in the southwest quadrant of the plots in the first row of the first column. There were three rows and three columns, all of which were also designated by number, beginning again in the south and west. Rows ran from west to east, with Row 1 at the highest point on the slope in the west, closest to the road. Columns were enumerated running from south to north, with Column 1 in the south, adjacent to the coffee plantation. Individual plots were numbered from one to sixty-three, with Plot 1 in the southwest corner (Block 1, Row 1, Column 1) and Plot 63 in the northeast corner (Block 9, Row 3, Column 3).

After blocking by variety as the main treatment, a second treatment set was applied within each individual block. This set of treatments consisted of two types of organic soil amendments, poultry manure and composted manure, each applied at four rates: 0 ton ha^{-1} (control), 1 ton ha^{-1}, 1.5 ton ha^{-1}, and 3 ton ha^{-1}. These rates were within the typical range of application rates, as expressed by survey respondents (Chapter 2). Each block was comprised of seven individual 2 x 3 m (6m^2) plots, each of which received one of the treatments at a given rate. For each block, only one control was used to represent the 0 ton ha^{-1} rate for both poultry manure and composted manure treatments. Amendment treatments and rates were randomized within each block using the random number method and Completely Randomized Design (CRD). A walking space of 1.5 m was created between all individual blocks to facilitate data collection and allow for the placement of black tarpaulin between rows. Black tarpaulin was installed on 1 June to prevent the movement of manure nutrients downslope between treatments.

Compost and manure applications. More than 100 kg of one-month old compost, derived from poultry manure and straw was collected on 30 May 2009 from two bins located near CAEC facilities and transported to an indoor storage facility and spread over 2 m² on a concrete floor for air drying until 6 June 2009. Compost was noted to have a characteristic black/brown color but some large debris from stock materials remained visible.

After drying, on 1 June 2009, compost was collected and weighed in sacks to 30 kg and transported to the field site. For the second treatment, an identical quantity of eight-month-old poultry manure was collected, weighed, and transported to the site. Birds from which the manure was derived were fed a diet of (by percentage) maize bran (58%), cotton seed cake (30%), fish (8%), shells (3%), a premix (0.5%), and salt (0.5). Bedding in the poultry unit consisted of coffee husks and wood shavings. Poultry manure had been stored outdoors and contained wood chips and other bedding material.

On 9 June 2009, amendment treatments were subsequently weighed out specifically for individual experimental plots (2 x3m) using an electronic balance. Beginning in the northeast, amendments for all individual plots were then applied to the middle of the specified plot and spread evenly across the plot with hand hoes. Dried residues of spear grass (*Imperta cylindrica*), couch grass (*Digiteria scalarum*) and Congo signal grass (*Brachiaria ruziziensis*) were spread evenly over all plots as mulch to protect recently applied amendments from solar radiation and volatilization.

Hand planting of amaranth seeds in experimental plots occurred on 10 June 2009. An average of 10 seeds was planted, following the traditional practice of planting in holes created with a stick approximately 1 cm deep. Seeds were immediately covered with soil. Sticks were also used both to mark borders between individual plots, as well as to measure distances between rows. For measuring intervals within rows, a 3-m length of string was held the length of each individual plot and tied with knots every 30 cm; the above procedure was then followed for each planting hole. Plants were watered following methods described above approximately every other day. Efforts were made by all involved parties to prevent intrusion by livestock living on-site at MUARIK. Particularly, this entailed the construction of fencing on two of the four open sides of the plots, adjacent to the road and the avocado grove. It was decided that the relatively dense stand of coffee plants to the south would impede access for both humans and livestock in this direction.

Data collection. Soil samples were taken on 26 June 2009 after clearing of banana pseudostems. The cleared area was divided into four equal quadrants. Soil cores were taken from the center of each quadrant, using a hand auger, to depths of 0-15 cm and 15-30 cm, and kept separately in individual plastic bags for each depth. Samples were subsequently air-dried indoors for three days and transferred to the Soil Science Laboratory at Makerere University for analysis. Soils were then analyzed for pH, soil organic matter (SOM), total nitrogen (TN), available phosphorus (P), exchanges bases of sodium (Na), potassium (K), magnesium (Mg), and calcium (Ca), and texture using standard procedures described in Okalebo et al. (1993).

Daily precipitation and temperature were recorded at the nearby MUARIK Weather Station, providing information on growing conditions for the entire course of the experiment.

Percent germination data were collected on 25 June 2009 and 1 July 2009 by assessing seed germination from each individual planting hole and recording germination as a binomial (yes or no) variable; the total number of holes with seeds germinated in each individual plot was then added to determine the percent germination for that plot, based on local protocols.

Experiment 2: On-Station Mid–Season Amaranth Production

Field preparation. A second experiment was initiated to the west and upslope from Experiment 1, in close proximity to the road, on 10 July 2009. Field preparation for Experiment 2 from 10 to 13 July 2009 consisted of the same procedures as Experiment 1, with the clearing of banana pseudostems, followed by disking and harrowing of the plots. Compost and poultry manure collection and handling on 11 July 2009 followed similar procedures as Experiment 1.

After final leveling and clearing of debris on 13 July, individual plots were established using the identical original design of Experiment 1. Soil amendments were applied to individual plots on 16 July 2009, as in the previous experiment. Concomitantly, black polythene tarp was installed lengthwise north-south between three block sets in order to prevent downslope leaching of nutrients.

Planting of grain amaranth on 17 June 2009 followed previously described methods. Newly planted seeds were irrigated manually on 18 July 2009 using water cans at a rate of approximately 9 L per individual 3 x 2 m plot. Irrigation of seeds and seedlings continued on a regular basis during plant growth, typically every one to two days by connecting hoses to a spigot near the poultry unit to the southeast. Flow of water from the hose was measured regularly to approximate irrigation rates per individual plot; given a flow rate of 0.33 L/sec and an average time of one and one-half hour to irrigate all plots, this provided an estimated average volume of 30 L applied to individual plots for each irrigation session.

Plants were thinned twice following germination, at 19 DAP (4 August 2009) and at 32 DAP on 17 August 2009, leaving three plants per hole. Plants were thinned to one plant per hole five weeks after planting. Thinning was conducted for the "golden" and "cream" varieties on the aforementioned dates while 'Plainsman' did not require thinning, due to poor germination and establishment of the latter. Attempts were also made on 17 August 2009 to transplant seedlings from holes with high germination rates to those with little or no germination; however, none of the 'Plainsman' transplants became established.

Weeding using a hand-hoe was conducted approximately every two weeks. Initial weeding of "cream" and "golden" blocks was conducted on 1 August 2009, followed by another weeding on 12 August 2009. Straw mulch from forage grass was applied in a 1-2 cm thick layer around each plant at the first weeding for all varieties. 'Plainsman' plants were weeded on 8 August 2009.

When insect pest populations were observed, insect management was obtained by spraying all upper and lower surfaces of amaranth leaves on 27 August 2009 with a commercially available neem extract formulation (Nimbecidine™; active ingredient azadirachtin, manufactured by PBT International LTD, North Potomac, MD, USA) diluted to a 1% concentration, and applied with a hand-pumped, backpack insecticide sprayer.

Data collection. Additional soil samples to determine baseline soil parameters were deemed unnecessary prior to beginning Experiment 2, as new plots were established adjacent to the original experiment. However, samples of poultry manure and composted manure were collected for analysis at the Soil Science Laboratory at Makerere University. Daily precipitation and temperature were recorded at the nearby MUARIK Weather Station, providing information on growing conditions for the entire course of the experiment.

A germination test was begun on 31 July 2009 under laboratory conditions in order to determine germination percentage under controlled conditions. This was accomplished by collecting 50 seeds of each of the three varieties and ensuring seeds were kept moist for several days.. Seeds were stored indoors at ambient temperatures (average high of 25° C and average low of 16° C for the Kampala area in August) for a period of ten days, at which point no new germination was occurring. Number of germinating seeds were subsequently tabulated and calculated as a percentage of the original seed count to determine percent germination.

Weed population counts were determined by randomly selecting three plots per treatment, for a total of 21 plots, and subsequently counting all weeds within 0.09 m^{-2} of a plant from the middle of the center row of the designated plot. Edges of the 0.09 m^{-2} space were then marked using sticks on each of the four sides; the number of weeds in this area was then tabulated visually. Weed population counts for Experiment 2 were conducted on 30 July 2009, 11 August 2009and 22 August 2009.

Insect populations were determined on 27 August 2009 for “cream” and “golden” varieties on the same number of plants assessed in the weed population counts described above by counting the total number of insects on all leaf surfaces. Insects were not classified by type.

Amaranth plant growth was determined by counting the number of leaves and measuring plant height (base of stem to plant apex) at 49-50 days after planting on ten plants in the middle of each individual plot. One height measurement was conducted on 4 September 2009 and a leaf count was conducted on 5 September 2009.

Plant harvest

Harvesting occurred on 9 October 2009 (91 DAP) by manually cutting plants with a sharp knife at the base of the inflorescence. For "golden" and "cream" varieties, ten plants from the middle row of each plot were selected for harvest and cut inflorescences from each individual plot were stored collectively in burlap sacks. Due to poor stand establishment and growth, 'Plainsman' seed heads were collected from only three plants from each individual plot. Individual sacks were then tied and transported to the MUARIK Dept. of Crop Science Store where seed heads were air-dried on the on top of the burlap sacks. Seed heads were subsequently air-dried by placement outdoors, under the sun, for six hours or more over the course of five days depending on daily weather conditions. During inclement weather, seed heads were stored indoors and continued drying until seed heads were completely dry and easily threshed. Seed heads from each plot were placed inside paper bags and hand-threshed to retain all seeds. In order to clean seeds of chaff and light, immature seeds, winnowing was conducted in a round, woven winnower, according to local protocols. Winnowed seeds were subsequently placed in polythene bags, locally known as black 'kavera', and labeled based with plot of origin.

After winnowing, grain samples (grain from ten plants per plot) were weighed using an electronic balance to obtain an average weight for each individual plot. For analysis of amaranth grain protein content, amaranth grain was ground into flour and packaged at Makerere University in the days just prior to 26 November 2009. Ground samples were then conveyed by air from Uganda to Iowa State University in Ames, Iowa, USA. Upon arrival, samples from individual 3x2 m plots were pooled by variety and treatment, with approximately 10g from each individual plot placed into each appropriate receptacle based on these criteria. Ground samples were then shipped to the laboratories of AIB International, Inc. (Manhattan, KS) and analyzed for protein content on 29 December 2009.

Experiment 3: On-Station Rainy Season Amaranth Production

Field preparation. Following the completion of Experiment 1, plots were cleared of amaranth plant residue and Experiment 3 was established in the same location with identical experimental design and plot layout. Plots were harrowed to prepare for planting on 23 September 2009 and again on 29 September 2009. The area was leveled in a similar manner as in Experiments 1 and 2 to ensure a uniform planting surface. Identical quantities of poultry manure and composted manure as in Experiments 1 and 2 were treated as previously described, and applied to the appropriate individual plots on 2 October 2009. On the same date, residue from congo signal grass (*Brachiaria ruziziensis*) and spear grass (*Imperata cylindrica*) was applied as mulch and spread over the plots, while a tarpaulin was placed between rows running north-south to prevent N leaching. Amaranth seeds of the same three varieties were planted on 3 October 2009 using previously described methods.

Cultivation. Plots were manually weeded on 14 October 2009 and on 30 October 2009. All plots were sprayed on the 30 October with neem extract. All plots received supplementary watering to ensure continued germination on 22 October 2009 and 23 October 2009.

Plantings were thinned twice: first to 3–5 plants per hole between 24 October 2009 and 25 October 2009, then to one plant per hole on 30 October 2009. During the second thinning, the individual plants were “hilled” or “mounded” with soil at the base to provide structural support for the growing plant.

Data collection. Daily precipitation and temperature were recorded at the nearby MUARIK Weather Station, providing information on growing conditions for the entire course of the experiment.

Weed counts for Experiment 3 were conducted as previously described on 11 October 2009, 30 October 2009 and 14 November 2009. Insects were assessed on 30 October 2009 using previously described methods on 6 November 2009, 14 November 2009, and 29 November 2009.

Plant height was measured on 6 November 2009, 21 November 2009, and 28 November 2009. Leaf number was assessed on 28 November 2009 following previously described methods.

Plant harvest. Harvesting occurred on different dates for each of the three varieties due to varietal differences in days to maturity and weather conditions. Both ‘Plainsman’ and “golden” varieties were determined to have reached maturity by 17 December 2009 (75 DAP). ‘Plainsman’ seed heads were harvested on 22 December 2009 (80 DAP) and “golden” was harvested on 30 December (88 DAP). The “cream” variety was later in reaching maturity and was harvested on 9 January 2010 (98 DAP), although time to maturity was probably closer to 90 DAP. Seed heads were harvested, dried, winnowed and stored as previously described.

For analysis of amaranth grain protein content, amaranth grain was ground into flour and packaged at Makerere University in the days just prior to 16 January 2010. Ground samples were then conveyed by air from Uganda to Iowa State University in Ames, Iowa, USA. Upon arrival, samples from individual 3x2m plots were pooled by variety and treatment, with approximately 10g from each individual plot placed into each appropriate receptacle based on these criteria. Ground samples were then shipped to the laboratories of AIB International, Inc. (Manhattan, KS) and analyzed for protein content on 29 March 2010.

Data analysis. Experimental data for all parameters, with the exception of yields were subjected to analysis of variance (ANOVA), and means were compared using Student's t at P<0.05 level of significance with JMP statistical software (Cary, NC). In light of the complexity of the Latin Square design, the JMP Fit-Model function with Standard Least Squares personality was used to increase the power of analysis where data was sufficient, notably for analysis of plant germination, leaf count, plant height, and grain yields.

Results and Discussion

Soils

Surface soils in the experimental area are clay loams and are likely ferralitic soils per USDA classification (1974) (Katuuramu, 2006). Soil samples from the experimental site were very acidic, with an average pH of 4.1 across all soil samples (Table 1). Soil pH was highest to the south and east and in the top 15 cm of the soil profile, with the highest recorded value of 4.8 for the upper 15 cm in southeast quadrant. The lowest pH of 3.6 was recorded in the northwest quadrant in the 15 to 30 cm depth interval. Soil pH on the experimental site was unusually low for the area, as the reported average pH for MUARIK as a whole is 6.0-7.0 (Katuuramu, 2006).

Similarly, data in the top 15-20 cm of soils in the Kampala area at Kawanda (deep, red, Buganda loam) and Bukalasa (deep, red, Buganda clay loam, 48km north of Kampala), tabulated by Jameson (1970), showed a pH of 6.1 and 6.4, respectively. Other studies with data for topsoils (0-15cm or 0-20cm) in Uganda, such as those by Esilaba et al. (2005) and Tumuhairwe et al. (2007) displayed similar pH values for other locations in Uganda. The pH values ranged between 5.0 and 5.5 in Mayuge District in eastern Uganda for the former case, while the latter found pH values between 5.8 and 6.6, with a reported mean of 6.3 for soils in the semi-arid Mubende District of western Uganda.

Soil organic matter (SOM) was low in the experimental area, with a mean value of 1.92% across all samples. The SOM was highest in the upper 15 cm of the southwest quadrant, with a value of 3.11% SOM. The lowest recorded value for soil organic matter was 1.02% for the 15-30 cm depth interval in the northeast quadrant.

The low values for SOM are typical of the area. For example, data for soils in the Kampala area at Kawanda and Bukalasa, tabulated by Jameson (1970), demonstrated soil organic carbon levels of 2.0% and 4.0%, respectively. Soil organic matter levels were also comparable to those found in Chapter 2 among 33 farmers in Kamuli District, where the mean was 2.49% SOM (standard deviation 0.94) for soils sampled to a depth of 15 cm.

Other studies with data for topsoils (0-15cm or 0-20cm) in Uganda, such as those by Esilaba et al. (2005) and Tumuhairwe et al. (2007) displayed similar SOM values for other locations in Uganda. These SOM values ranged between 2.16% and 2.84% in Mayuge District in eastern Uganda for the former case, while the latter found SOM values between 2.88% and 6.50%, with a reported mean of 4.31% for soils in the semi-arid Mubende District of western Uganda.

Soil nitrogen was concomitantly lacking in these soils, with a mean of 0.13% and the highest value of 0.19% in the top 15 cm of the southwest quadrant. The lowest value was 0.10% N, which was recorded in three instances for the 15 to 30 cm interval samples, in the southwest, northeast, and northwest quadrants. Average phosphorus values were low overall, but were highest in the 0 to 15 cm interval of the northeast quadrant with a value of 18.25 mg kg^{-1} P. The lowest P concentration recorded was 3.22 mg kg^{-1} in the 15 to 30 cm interval of the northwest quadrant. The average P for all samples was 6.91 mg kg^{-1}.

Low nutrient concentrations are typical of the area and the TN and P levels were comparable to those found in Chapter 2 among 27 farmers in Kamuli District, where the means were 0.12% N and 8.70 mg kg^{-1} P (standard deviations of 0.05 and 6.69, respectively) for soils sampled to a depth of 15cm.

Data on soils in the Kampala area at Kawanda and Bukalasa, tabulated by Jameson (1970), demonstrated comparable levels of nitrogen and phosphorus. The TN was found to be 0.14% and 0.25% for the respective locations, while phosphorus concentration was 27 mg kg^{-1} P and 37 mg kg^{-1} P.

Other studies with data on topsoils (0-15cm or 0-20cm) in Uganda, such as those by Esilaba et al. (2005) and Tumuhairwe et al. (2007) displayed similar TN and P values for other locations in Uganda. The TN values were reported as 1.0% in Mayuge District in eastern Uganda for the former case, while the latter found TN values between 0.10% and

0.20%, with a reported mean of 0.16%, for soils in the semi-arid Mubende District of western Uganda. Values for P ranged from 1.9 mg kg^{-1} P to 4.6 mg kg^{-1} P in the former case, and ranged from 3.02 mg kg^{-1} P to 9.42 mg kg^{-1} P, with a reported mean of 5.11 mg kg^{-1} P, in the latter.

Values for the four major soil cations, potassium, sodium, calcium, and magnesium, were also low. Potassium ranged from 1.35 $Cmoles_c$ kg^{-1}K in the top 15 cm in the southeast quadrant to 0.29 $Cmoles_c$ kg $-^{1}$ for the 15 to 30 cm interval in the northeast, with a mean for all samples of 0.66 $Cmoles_c$ kg^{-1} K. Sodium ranged from a maximum of 0.08 $Cmoles_c$ kg^{-1} Na in the northeast 15 to 30 cm interval to a minimum 0.05 $Cmoles_c$ kg^{-1} Na for the 15 to 30 cm interval in all other quadrants; the mean sodium value for samples was 0.06 $Cmoles_c$ kg^{-1} Na. Calcium values ranged from a high of 4.5 $Cmoles_c$ kg^{-1} Ca in the top 15 cm of soil in the northwest to a low of 1.2 $Cmoles_c$ kg^{-1} Ca for the 15 to 30 cm sampling depth in the northeast; the mean calcium value for all samples was 3.0 $Cmoles_c$ kg^{-1} Ca. The highest recorded value for magnesium was 1.69 $Cmoles_c$ kg^{-1}Mg for the upper 15 cm in the southeast, while the lowest was 0.65 $Cmoles_c$ kg^{-1} Mg at 15-30 cm in the northeast quadrant. The mean recorded magnesium value was 1.15 $Cmoles_c$ kg^{-1} Mg. Tabulating the foregoing exchangeable cations provides an approximate total of exchangeable bases of 7.5 $Cmoles_c$ kg^{-1} for the upper 15 cm in the southeast, and a minimum of 2.22 $Cmoles_c$ kg^{-1} in the northeast. Mean exchangeable bases for all samples was 4.86 $Cmoles_c$ kg^{-1}.

Values for the major soil cations were comparable to those found in Chapter 2 among 27 farmers in Kamuli District, where mean values were 0.95 $Cmoles_c$ kg^{-1} K (standard deviation - 0.77), 0.09 $Cmoles_c$ kg^{-1}Na (standard deviation – 0.02), 5.33 $Cmoles_c$ kg^{-1} Ca (standard deviation – 1.46), 1.78 $Cmoles_c\ kg^{-1}$ Mg (standard deviation – 0.68), and total exchangeable bases of 8.16 $Cmoles_c\ kg^{-1}$ (standard deviation – 2.10).

Data on soils in the Kampala area at Kawanda and Bukalasa, tabulated by Jameson (1970), demonstrated comparable levels for the exchangeable cations, with the exception of Na. At Kawanda, exchangeable cations were reported as 0.5 $Cmoles_c\ kg^{-1}$ K, 4.2 $Cmoles_c\ kg^{-1}$ Ca, and 2.0 $Cmoles_c\ kg^{-1}$ Mg. Bukalasa samples displayed exchangeable cation values of 1.3 $Cmoles_c\ kg^{-1}$ K, 10.0 $Cmoles_c\ kg^{-1}$ Ca, and 3.0 $Cmoles_c\ kg^{-1}$ Mg.

Other studies with data on top soils (0-15cm or 0-20cm) in Uganda, such as those by Esilaba et al. (2005) and Tumuhairwe et al. (2007) display similar levels of exchangeable cations for other locations in Uganda. In the former case, exchangeable cation values in Mayuge District in eastern Uganda were reported to range from 1.51 to 2.46 $Cmoles_c\ kg^{-1}$ K, 3.52 to 5.36 $Cmoles_c\ kg^{-1}$ Ca, 0.39 to 0.62 $Cmoles_c\ kg^{-1}$ Na, and 1.92 to 2.97 $Cmoles_c\ kg^{-1}$ Mg. For soils in the semi-arid Mubende District of western Uganda, the latter study found mean exchangeable cation values of 0.89 $Cmoles_c\ kg^{-1}$ K, 7.34 $Cmoles_c\ kg^{-1}$ Ca, 0.11 $Cmoles_c\ kg^{-1}$ Na, and 1.27 $Cmoles_c\ kg^{-1}$ Mg.

Soil fine earth fraction values for sand, silt, and clay were variable. Sand content was highest in the top 15 cm northwest quadrant, where the soils were 56% sand. The upper 15 cm of the southwest quadrant had the least sandy soils, with a value of 32% sand. Average sand content for al samples was 43%. Clay content ranged from a high of 48% in 15 to 30 cm interval of the northeast, to a low of 14% in the upper 15 cm in the northwest; average clay content was 33% for all samples. The highest silt content was recorded as 36% in the upper 15 cm of soil in the southwest, while the lowest occurred in the northeast, where both depth intervals contained 16% silt. Mean silt content for all samples was 24%.

Compared to soils discussed in Chapter 2 obtained from 27 farmers in Kamuli District, soils from the experimental site had relatively a relatively high proportion of clay, as Kamuli soils had a mean clay content of 22% (standard deviation of 7) and concomitantly higher proportion of sand, with a mean of 62% sand (standard deviation of 9).

Precipitation and temperature

Daily precipitation and temperature between May and December 2009 were quite variable (Table 2). Total rainfall during the experiment (June-December) was 800 mm, with a monthly average of 124 mm. Highest rainfall occurred in October (190mm), while the lowest was in November (54.5mm). The total and monthly average precipitation was higher than the Kampala average of 615mm total rainfall for the period of the study (Table 2), or a monthly average of 88mm. The 2009 rainfall in Kabanyolo was higher than the monthly averages for the Kampala area, with slightly more precipitation in June and July than the average. Precipitation in August, September, and October was much higher than the average for these months, while precipitation in November and December was below monthly averages.

Soil amendments

Nutrient content (N–P–K) was higher for the poultry manure compared to the composted manure, which averaged 1.3% N, 0.55 mg kg^{-1} P, and 1.02 $Cmoles_c$ kg^{-1} K (Table 4). Composted manure maintained a nutrient content of 0.54% N, 0.20 mg kg^{-1} P. and 0.88 $Cmoles_c$ kg^{-1} K. Nutrient content of the uncomposted poultry manure appears to have decreased somewhat from a previous analysis of the same manure pile by Dr. Zake of

Makerere University who found values of 2.3% N, 1.9 mg kg^{-1} P. and 1.1 $Cmoles_c$ kg^{-1} K (Naakubuza, pers. comm.). Such a decrease in N and P is not unexpected, given that the poultry manure pile was kept outdoors with no roofing and exposed to the elements. In tandem with the lack of roofing, storage of the poultry manure on bare ground, as opposed to an impermeable surface, may have facilitated the downward leaching of nutrients, particularly nitrogen.

Nitrogen, phosphorus, and potassium values for both poultry manure and composted manure were within the range of values reported by Lekasi et al. (2003) in a survey of cattle manure quality among 300 smallholder farmers in central Kenya. The study demonstrated mean values across all manure samples of 1.12% N, 0.30 mg kg^{-1} P, and 2.38 $Cmoles_c$ kg^{-1} K, with standard deviations of 0.33, 0.11, and 1.06, respectively.

The literature on amendment quality indicates that the foregoing nutrient values are low in comparison to values for poultry manure in the US, where data compiled from numerous sources by Brady and Weil (1999) indicated average nutrient values for poultry manure as 4.4% N, 2.1 mg kg^{-1} P, and 2.6 $Cmoles_c$ kg^{-1} K. For compost, the foregoing value of 0.54% is within the typical range of composts in the US (0.5-2.5% N), but is on the low end of the spectrum. Similarly, values for P are considered low by US standards according to Sanchez (2009), while the reported K value is comparable with those found in the US. However, it should be noted that manure and compost quality are highly variable, even within individual samples, depending on a number of exogenous factors, and accurate values are difficult to obtain (Brady and Weil, 1999; Davis et al., 2002; Sanchez, 2009).

Plant Data

Despite fencing efforts, cattle from a nearby farm entered the experimental plots (Experiment 1) through the coffee grove and consumed a large number of amaranth plants on 8 July 2009. Destruction of the plants was concentrated around the edges and in plants in Row 3. Greatest damage was observed in Block 7 of Column 1, Row 3. Following this incident, plant data was not collected in Experiment 1 except for plant germination data. Plant growth data was collected in Experiments 2 and 3, and is described below.

Plant germination and emergence

For the controlled germination test, the "golden" variety had the highest germination rate, at 90%, followed by the "cream" variety at 80%, and 'Plainsman' at 70%.

In-field plant emergence was not significantly different between amendment treatments on either 25 June 2009 (P=0.1592) or 1 July 2009 (P=0.3531) (Table 3). Mean emergence was 51.9% on 25 June 2009 and 68.7% on 1 July 2009. Percent emergence on 25 June 2009 was significantly greater for "cream" and "golden" varieties compared to 'Plainsman' (P=0.0377). On 25 June 2009, mean emergence was 68.1% and 55.7% for "golden" and "cream", respectively, while emergence for 'Plainsman' was 32.1%. On 1 July 2009, percent emergence was not significantly different between varieties (P=0.3958), with percent emergence of 76.2% for both "golden" and "cream" varieties, while 'Plainsman' emergence was 53.8%.

The foregoing information indicates significant differences in seed quality and environmental sensitivity between varieties at the critical seedling and establishment phase, portending major impact on amaranth grain yields. The experiments would, therefore, have been more useful for comparing varieties if the seed lots were equally healthy.

Weed populations

Experiment 2. Weed populations on 30 July 2009 were not significantly different between amendment treatments (P=0.0845) (Table 5); the highest mean weed population by treatment was 90 weeds 0.09 m^{-2} for poultry manure at the 1 ton ha^{-1} rate, while the lowest mean was 40 weeds 0.09 m^{-2}, which occurred in plots treated with 1 ton ha^{-1} of compost. Weed counts on 11 August 2009 (P=0.6542) and on 22 August (P=0.6952) also were not significantly different between amendment treatments. On 11 August 2009, the highest mean weed population by treatment was 90 weeds 0.09 m^{-2} for compost at the 1 ton ha^{-1} rate, while the lowest mean was 40 weeds 0.09 m^{-2}, which occurred in control plots. On 22 August 2009, the highest mean weed population by treatment was 100 weeds 0.09 m^{-2} for compost at the 1 ton ha^{-1} rate, while the lowest mean was 72 weeds 0.09 m^{-2}, which occurred in plots receiving either 1 ton ha^{-1} or 1.5 ton ha^{-1} of compost.

Experiment 3. The mean weed population across all treatments and varieties was 18.5 weeds 0.09 m^{-2}on 11 October 2009. Weed population was not significantly different between treatments (P=0.5770) (Table 11), rows (P=0.9424), or columns (P=0.2901) (Table 12). By treatment, the highest mean weed populations were recorded at 31.7 weeds 0.09 m^{-2} for plots receiving 1.5 ton ha^{-1} poultry manure, while the lowest weed populations were recorded at 9.7 weeds 0.09 m^{-2} for 3 ton ha^{-1} compost. The mean weed population across all treatments and varieties was 43.6 weeds 0.09 m^{-2} on 30 October 2009. Weed population was not significantly different between treatments (P=0.3927) (Table 11), rows (P=0.1871), or columns (P=0.3667) (Table 13). By treatment, the highest mean weed populations were recorded at 65.0 weeds 0.09 m^{-2} for plots receiving 3 ton ha^{-1} poultry manure, while the lowest weed populations were recorded at 13.3 weeds 0.09 m^{-2} for 1 ton ha^{-1} compost. The mean weed population across all treatments and varieties was 69.3 weeds 0.09 m^{-2} on 14 November 2009. Weed population was not significantly different between treatments (P=0.1429) (Table 11), rows (P=0.4403), or columns (P=0.6571) (Table 12). By treatment, the highest mean weed populations were recorded at 126.7 weeds 0.09 m^{-2} for plots receiving 1 ton ha^{-1} poultry manure, while the lowest weed populations were recorded at 46.3 weeds 0.09 m^{-2} for 3 ton ha^{-1} poultry manure.

Insect populations

Experiment 2. Insect populations counted on plants on 27 August 2009 were not significantly different between amendment treatments (P=0.5049) or varieties (P=0.7115) (Table 6). The highest mean insect population by amendment treatment was 22 insects $plant^{-1}$ for the 1 ton ha^{-1} of poultry manure, while the low was 1.3 insects $plant^{-1}$ for the 3 ton ha^{-1} poultry manure treatment. Across varieties, means of 4.6 insects $plant^{-1}$ were recorded for the “cream” variety while 6.8 insects $plant^{-1}$ were observed on the “golden” variety. Although insects were not counted according to genera, some of the insects found on amaranth plants included the brown stink bug (*Euschistus* spp.), aphids (*Aphis* spp.), brown marmorated stink bug (*Halyomorpha halys*), and lygus bug (*Lygus lineolarius*).

Experiment 3. The mean insect population number for amaranth plants censused on 6 November 2009 was 15.0 insects $plant^{-1}$, which was not significantly different between amendment treatments (P=0.6849) or varieties (P=0.0663) (Table 13). Insect numbers ranged from 22 insects plant^{-1} for the 1 ton ha^{-1} of poultry manure treatment to 1.3 insects plant^{-1} for the 3 ton ha^{-1} poultry manure treatment. Insect population counts by variety ranged from 36.8 insects plant^{-1} for the “cream” variety and 40.1 insects plant^{-1} for the “golden” variety. Insect numbers for ‘Plainsman’ variety were not included in the analysis given its poor stand establishment and growth. Insect populations were not significantly different between rows (P=0.2287) or columns (P=0.4932) (Table 14).

The mean insect population number for amaranth plants counted on 14 November 2009 was 32.7 insects plant^{-1} and was not significantly different between amendment treatments (P=0.7682) or varieties (P=0.2988) (Table 13). Insect populations ranged from 48.7 insects plant^{-1} for the 1.5 ton ha^{-1} of compost to 13.7 insects plant^{-1} for the 1.5 ton ha^{-1} poultry manure treatment. Insect population counts by variety ranged from 36.8 insects plant^{-1} for “cream” and 40.1 insects plant^{-1} for “golden”. Insect populations were not significantly different between rows (P=0.8523) or columns (P=0.4711) (Table 14). The mean insect population number for amaranth plants counted on 29 November 2009 (Table 13) was 56.6 insects plant^{-1} and was not significantly different between amendment treatments (P=0.5391) or varieties (P=0.7395). The range was 104.0 insects plant^{-1} for the control to 30.7 insects plant^{-1} for the 1.5 ton ha^{-1} poultry manure treatment. Insect population counts by variety ranged from 64.0 insects plant^{-1} for “cream” to 6.8 insects plant^{-1} for “golden”. Insect populations were not significantly different between rows (P=0.1853) or columns (P=0.4299) (Table 14). Although insects were not counted according to genera, the suite of insects found on amaranth plants in Experiment 3 was generally the same as those in Experiment 2.

Plant height

Experiment 2. Plant height as measured 8 wk after planting on 4 September 2009 was significantly different between varieties, with “golden” and “cream” significantly taller than ‘Plainsman’ (*P*=0.0042) (Table 7), but not between amendment treatments (*P*=0.6366) or columns (*P*=0.7624). Mean plant height was 115 cm and 116 cm for “golden” and “cream” varieties, respectively, while the mean height for ‘Plainsman’ was significantly lower at 75.5 cm. Mean plant height ranged from 107 cm for plants receiving the 1.5 ton ha^{-1} compost treatment to 97.9 cm in plants receiving the 1 ton ha^{-1} compost and 1 ton ha^{-1} poultry manure treatments on 9 September 2009.

Experiment 3. Plant height on 6 November 2009 was significantly different between varieties (*P*=0.0171) (Table 15), but not between amendment treatments (*P*=0.9304). Mean plant height was 68.9 cm, 44.2 cm, and 59.1 cm for “golden”, “cream” and ‘Plainsman’, respectively. Plant height for ‘Plainsman’ and “golden” was significantly higher than for cream comparing means with Student’s t. Plant height was also significantly different between columns, with height for Column 1 significantly greater than Column 2 and Column 3 (*P*=0.0370). Mean plant height ranged from 60.1 cm for plants receiving the 1 ton ha^{-1} poultry manure treatment to 55.1 cm for plants receiving the 3 ton ha^{-1} compost treatment.

Plant height as measured on 21 November 2009 was not significantly different between varieties (*P*=0.0546), amendment treatments (*P*=0.5160), or columns (*P*=0.2374). Mean plant height was 109.5 cm, 82.7 cm, and 85.7 cm for “golden”, “cream” and ‘Plainsman’, respectively. Mean plant height ranged from 97.9 cm for plants receiving the 3 ton ha^{-1} compost treatment to 86.2 cm for plants receiving the 1.5 ton ha^{-1} compost treatment.

Plant height on 28 November 2009 was significantly different between varieties (*P*=0.0325), but not between amendment treatments (*P*=0.7786) or columns (*P*=0.1830). Mean plant height was 125.8 cm, 110.7 cm, and 92.7 cm for “golden”, “cream” and ‘Plainsman’, respectively. Mean plant height ranged from 117.7 cm for plants receiving the 1.5 ton ha^{-1} poultry manure treatment to 104.1 cm for plants receiving the 1.5 ton ha^{-1} compost treatment.

Mean amaranth plant height values for the on-station experiments were higher than those found by Nyankanga (2008) in a study conducted in Kisumu district of western Kenya near Lake Victoria, where he reported plant height values of 8.2 to 74.4 cm after eight weeks for plants receiving chemical fertilizer. Plant height ranged from12.6 to 32.1cm for plots treated with cattle manure. A comprehensive study by Gupta et al. (1992) assessing the impact of numerous parameters on amaranth grain yields at four locations in Kenya displayed wide variation in amaranth plant heights at maturity. A variety trial of ‘medium-maturing’ amaranth (70 to 90 days) was conducted at Kabete, the site with the most comparable climatic conditions of the Uganda locations studied (elevation of over 1000 m, with 800 mm precipitation during the short rains and average monthly temperatures between 17.9° and 18.1°C), found plant height ranged between 117 cm and 183 cm during the short rains. This experiment showed that, during the long rains, plant height was highest for late-maturing varieties (over 100 days), with values for these varieties ranging between 188 cm to 218 cm at Kabete, while early-maturing varieties ranged between 53 cm and 77 cm.

A study conducted by Olaniyi (2007) in southwest Nigeria, an area with similar climate to central Uganda (albeit with higher temperatures and precipitation), on sandy loam soils (83% sand) with similar chemical properties to those in Kabanyolo (pH of 7.5, 2.85%

SOM, 0.14% N, 10.03 mg kg^{-1} P, 0.22 $Cmoles_c$ kg^{-1} K, 5.5 $Cmoles_c$ kg^{-1} Ca, 0.32 $Cmoles_c$ kg^{-1} Na, and 4.2 $Cmoles_c$ kg^{-1} Mg), receiving a basal N-P-K fertilizer side-dressing of 15-15-15 ha^{-1} demonstrated lower plant height values than those found at Kabanyolo. The study was conducted over two years during both the short and long rains and found, after eight weeks, plant height ranging from 46.4 cm and 89.9 cm in 2003 and from 44.8 cm to 85.6 cm in 2004.

Plant leaf number

Experiment 2. Plant leaf number on 5 September 2009 was significantly different between varieties (P=0.0004) (Table 7), but not between amendment treatments (P=0.5233) or columns (P=0.6857). Mean plant leaf number was 79.4 leaves $plant^{-1}$ and 50.8 leaves for “golden” and “cream” varieties, respectively, while the mean plant leaf number for ‘Plainsman’ was significantly greater at 139 leaves $plant^{-1}$. Comparison of means for each pair indicates that ‘Plainsman’ had significantly more leaves than both “golden” and “cream”, while the average number of leaves for the “golden” variety was significantly greater than for “cream”. For amendment treatments, plant leaf numbers ranged from 103 leaves $plant^{-1}$ in the control plots to 75.5 leaves $plant^{-1}$ in the 1.5 ton ha^{-1} poultry manure plots.

Experiment 3. Plant leaf number as measured on 28 November 2009 was significantly different between varieties (P=0.0176) (Table 16), but not between amendment treatments (P=0.9423) or column (P=0.5264). Mean plant leaf number was 79.4 leaves $plant^{-1}$, 50.8 leaves $plant^{-1}$, 135.4 leaves $plant^{-1}$ for “golden”, “cream” and ‘Plainsman’, respectively.

Comparison of means for each pair indicated that ‘Plainsman’ had significantly more leaves than both “golden” and “cream”. For amendment treatments, plant leaf number ranged from 103.2 leaves plant^{-1} for the control plots to 96.0 leaves plant^{-1} for both the 1 ton ha^{-1} and 3 ton ha^{-1} rates of poultry manure.

Amaranth leaf number in Kabanyolo was higher than values found by Olaniyi (2007) under similar climatic and agro-ecological conditions in southwest Nigeria, where leaf number ranged from 20.4 to 30.8 leaves plant^{-1} at 8 wk after planting, depending on year and variety. Leaf number was also higher than those generally found in the literature on vegetable amaranths. Vegetable amaranths are harvested for their leaves, and as such, are harvested in an earlier period than grain amaranth. For example, a study by AdeOluwa (2009) in southwest Nigeria recorded amaranth leaf number from 11 to 14 leaves plant^{-1}, averaged across different fertilizer types and harvested after four weeks.

Amaranth grain yields

Experiment 2. Lodging of plants due to severe weather was reported for Experiment 2, as was interference from birds with amaranth plants and grains. The mean amaranth grain yield for all treatments and varieties was 1110.4 kg ha^{-1}, with a standard deviation of 226.8 kg ha^{-1} (Table 8). Yields were significantly different between varieties (P=0.0083), as yield of the “golden” and “cream” varieties, with means of 1207.7 kg ha^{-1} and 1013.1 kg ha^{-1}, respectively, were significantly higher than yields of ‘Plainsman’. Yields from the ‘Plainsman’ variety were adjusted to account for low plant populations at harvest (four plants per individual plot, on average), though grain yields for individual plants was relatively high based on a harvest of three plants from each plot containing ‘Plainsman’, providing an average yield of 194.1 kg ha^{-1}.

Amaranth grain yields were not significantly different between amendment treatments (P=0.5657), but there was trend towards higher yields in plots receiving 1 ton ha^{-1} poultry manure, where yields averaged 1208.1 kg ha^{-1}. Control plots averaged 988.7 kg ha^{-1}. Yields were not significantly different between rows (P=0.3991). The mean grain yield for amaranth plants was 1043.9 kg ha^{-1} for Row 1, 1189.6 kg ha^{-1} for Row 2, and 1097.8 kg ha^{-1} for Row 3. Yields were also not significantly different between columns (P=0.6813). Mean grain yields for amaranth plants was 1109.6 kg ha^{-1} for Column 1, 1146.1 kg ha^{-1} for Column 2, and 1075.6 kg ha^{-1} for Column 3 (Table 9).

Experiment 3. The mean amaranth grain yield for all treatments and varieties was 1886.0 kg ha^{-1}, with a standard deviation of 921.1 kg ha^{-1} (Table 8). Yields were significantly different between varieties (P=0.0043), with yields of the “cream” variety, at 2750.2 kg ha^{-1}, significantly greater than the “golden” (1742.3 kg ha^{-1}) and ‘Plainsman’ (1165.6 kg ha^{-1}) varieties.

Amaranth grain yields were not significantly different between amendment treatments (P=0.2990), but there was trend towards higher yields in plots receiving 1.5 ton ha^{-1} poultry manure, where yields averaged 2701.2 kg ha^{-1}. Plots receiving 1 ton ha^{-1} poultry manure averaged 1857.2 kg ha^{-1}. Yields were significantly different between columns (P=0.0494), with the mean grain yields for amaranth plants recorded as 1708.6 kg ha^{-1} for Column 1, 2306.5 kg ha^{-1} for Column 2, and 2723.5 kg ha^{-1} for Column 3. Comparison of means indicates that yields for Column 3 were significantly greater than those in Column 1, while yields were not significantly different between Column 1 and Column 2, or Column 2 and 3 (Table 9).

As demonstrated by the foregoing data, yields were higher for Experiment 3 than Experiment 2, probably because Experiment 2 was initiated during the dry season, while Experiment 3 was conducted during the short rainy season. Such a result is not expected, given that precipitation is generally the factor most limiting plant productivity in tropical agro-ecosystems. Further, as discussed by Sanchez (1976), the onset of the rains often results in a ‘flush’ of nitrogen and other plant nutrients. Nitrogen is usually considered the most limiting plant nutrient for most crops and agroecosystems, and increased soil nitrogen availability and nitrogen fertilization has been widely shown to have positive effects on yields for amaranth and other crops (Apaza-Gutierrez et al., 2002; Bressani et al., 1987; Elbehri et al., 1993; Myers, 1998, Nyankanga, 2008).

The foregoing begs the question as to why organic soil amendment treatments failed to significantly increase amaranth grain yields. There are number of possible explanations. Firstly, however, it should be noted that the amendment application rates were identical to those used by Nyankanga (2008), who found that higher applications rates for cattle manure increased grain yield significantly. Such information indicates the existence of other confounding factors and one possibility is that, given the relatively lower yields displayed by the Nyankanga study, the Kisumu site may have had lower levels of soil nutrients compared to those found at Kabanyolo. Under such circumstances, cattle manure applications may display exponentially greater impact on grain yield.

Other explanations for the lack of treatment effect include the possibility that, as discussed above, soil amendment quality was too low to adequately supply plant nutrients.

Similarly, the Kabanyolo site had been under perennial vegetation for an extended period of time and, therefore, had probably not been tilled for some years. The release of plant nutrients associated with intensive tillage, conducted prior to initiation of the experiments, could have masked the impact of increased nutrient supply from soil amendments.

An unusually low soil pH may have inhibited microbial activity, particularly that of autotrophic bacteria responsible for nitrification, forestalling mineralization of N from amendments and, thus, rendering it unavailable to amaranth plants. This hypothesis receives some support in the literature, as a study by Ste-Marie and Paré (1999) examining the effects of vegetation, pH, and N availability on nitrification corroborates that nitrification is suppressed at low pH, finding no net nitrification occurring below pH 4.5. Further, the lower limit for autotrophic nitrification in forest systems appears to exist between pH values of 4.0 and 4.7 (Sahrawat, 1982; De Boer et al., 1989). This trend appears to be exacerbated where C:N ratios are high (Ste-Marie and Paré, 1999).

Interestingly, grain yield for the “cream” variety was significantly higher than “golden” in Experiment 3, while the opposite was true in Experiment 2. However, while both experiments demonstrated significant differences in yield between varieties, these differences were more pronounced in Experiment 3. While for Experiment 2 mean yield of “golden” was slightly less than 200 kg ha^{-1} greater than values for “cream” (P=0.0041), the mean grain yield for “cream” was 1000 kg ha^{-1} more than “golden” in Experiment 3, with a corresponding lower P-value (P=0.0002).

However, it should be noted that variability in yield also increased between Experiment 2 and Experiment 3. For Experiment 2, standard deviation of “cream” was 218.3 kg ha^{-1} and “golden” was 194.6 kg ha^{-1}, while the respective numbers in Experiment 3 were

846.8 kg ha^{-1} for “cream” and 718.6 kg ha^{-1} for “golden”. The error term in Experiment 3 was similarly inflated over that of Experiment 2, as the standard error for Experiment 2 was 45.1, compared to 171.4 for Experiment 3.

Based on the foregoing data, therefore, one may hypothesize that “golden” has greater drought tolerance than the “cream” variety. Similarly, yields for “golden” appear to be less variable than those for “cream”, as displayed by lower standard deviations in both on-station experiments. Indeed, yield for the “golden” variety increased by 44% (~500 kg ha^{-1}) between Experiment 2 and Experiment 3, compared to a yield bump for “cream” of more than 1700 kg ha^{-1} or 168%. However, conclusions regarding drought tolerance of Uganda amaranth varieties should be treated with precaution, as August and September 2009 both received a large amount precipitation.

Given that growing conditions were driest during the seedling and establishment phase of Experiment 2, seasonal yield differences may due to differential drought tolerance of seedlings of each variety rather than drought tolerance *per se*. Similarly, grain amaranth reportedly performs better during the short rainy season than the long rainy season (Masinde, pers. comm.), as intense weather events associated with the latter increase lodging and can exacerbate sprouting, molding and weathering of the grain as the plant matures. By the same token, as amaranth plants mature, water requirements are known to decrease while increases in solar radiation, temperature and photosynthesis are beneficial to yields (Putnam, 1990).

The significant differences in mean yields by column are more difficult to explain than the foregoing differences. Given that no significant differences were shown for insect and weed counts for any parameters in both Experiment 2 and Experiment 3, pest pressure does not appear to provide an explanation for these differences.

Experiment 2 demonstrated no clear relationship between yields and columns. Again, the evidence here does seem to corroborate a greater drought tolerance for the “golden” variety against the “cream”. Plot-level variation in yield trends vis-à-vis variety is likely related to differences in on-site microtopography and variation in soil physical properties. The on-site soil samples (Table 1) indicate a trend of increasing sand content, from south to north (Column 1 to Column 3), in the upper 15cm of the soil. By contrast, sand content in the 15 to 30 cm sampling interval increases in comparison to the 0 to 15 cm interval for the samples taken in the south, but decreases between sampling depth intervals in the north, with a concomitant increase in clay content, particularly for the sample taken in the northwest.

Given that grain amaranth tends to grow best on well-drained soils (Putnam, 1990), on-site variability in the fine earth fraction could potentially account for the seasonal variation in yields between columns. Particularly, soil physical properties could affect soil water-holding capacity and soil moisture and, as a result, plant available water. During the dry season, higher sand content may be detrimental plant growth due to associated reduction in water-holding capacity, while during the wet season higher sand content may have beneficial impacts on plant growth by reducing water logging and increasing infiltration, particularly when precipitation events are intense.

Similarly, higher clay content in the topsoil could have beneficial impacts during the dry season, but may be negative in the wet season due to reduced infiltration capacity and associated potential water logging. However, clay content does not appear to provide explanation in this instance, as this variable was relatively similar for the top 15cm from south to north, particularly where seasonal yield differences were greatest (in the northeast and southeast). This portends the potential importance of sand content in the upper 15cm.

On-site differences in the degree of clay illuviation which, in lieu of the 15-30 cm samples, appears to increase going northwest, may be also be of interest.

In relation to this, plot-level variation in soil physical properties may impact plant root development and, concomitantly, yields. This may be especially true for a deep-rooted crop like grain amaranth that maintains a long taproot and extensive lateral root system (Johnson and Henderson, 2002). Research in North Dakota by Johnson and Henderson (2002) demonstrated the importance of adequate soil moisture during establishment and vegetative stages, while also indicating that high soil moisture during establishment tends to inhibit deep root penetration and vegetative growth but not grain yield. The same study indicates that grain amaranth typically responds to soil water stress by increasing root depth and extracting soil water from deeper in the soil profile.

Amaranth grain yields reported in the literature exhibit a large degree of variability depending on such factors as soil chemical and physical properties, climate, planting density, planting time, variety, and level of fertilization. Although most studies containing data on amaranth grain yield do not include information on soil chemical and physical properties, amaranth grain yields from the Kabanyolo experiment are comparable to those found in the literature. Nyankanga's (2008) study in the Kisumu district of western Kenya near Lake Victoria demonstrated yields of 50 kg ha^{-1} at an application rate of 0.5 ton ha^{-1}; 110 kg ha^{-1} at 1 ton ha^{-1}; 250 kg ha^{-1} at 2 ton ha^{-1}; and 1500 kg ha^{-1} at 3 ton ha^{-1}.

The study by Gupta et al. (1992) in assessing the impact variety, date of planting, varietal days to maturity, season ('long' or 'short' rains), planting density, and fertilization on amaranth grain yields at four locations in Kenya found amaranth grain yields ranging from 70.7 to 714.0 kg ha^{-1} at a planting density of 66,666 plants/ha (70cm between rows, 20 cm within rows). It should be noted, however, that the experiment applied synthetic fertilizer at rates of 21 kg N/ha and 53 kg P_2O_5/ha. Medium-maturing varieties in this study, maturity dates similar to the "cream and "golden" varieties, tended to have higher yields compared to early- and late-maturing varieties under standardized conditions at Kabete, as yields ranged from 290 kg ha^{-1} to 1020 kg ha^{-1} for early-maturing varieties.

Yields from Kabanyolo also compared well with results from Gupta et al. (1992) testing the effects of planting date on two high yield, early- to medium-maturing *A. hypochondriacus* varieties, named '1023' and '1024'. Yields tended to decrease with a later planting date, as '1023' yielded between 1157.1 and 1481.6 kg ha^{-1} when planting during the first and second week of the short rains, respectively, while '1024' yielded between 1171.6 and 1484.1 kg ha^{-1} for the same parameterization. The experiments were again standardized with synthetic fertilizer at application rates of 21 kg N/ha and 53 kg P_2O_5/ha.

Yields for the two varieties in absence of standardization with fertilizers were tested during the short rains at Kabete, with plots receiving either the standard 21 kg N/ha and 53 kg P_2O_5/ha or no fertilizer (control). Fertilized plots of both '1023' and '1024' yielded 2500 kg ha^{-1}, while unfertilized plots demonstrated yields of 800 kg ha^{-1} for '1023' and 1000 kg ha^{-1} for '1024'.

In the study conducted by Olaniyi (2007) in southwest Nigeria, amaranth yields were generally lower than those achieved at Kabanyolo. Depending on year and variety, grain yields from the study ranged from 400 to 1500 kg ha^{-1}.

In the US, amaranth grain yields typically range from 700 kg ha^{-1} to 1700 kg ha^{-1}, while higher yields have been achieved internationally. Grain amaranth breeding programs in

Latin America have achieved yields of 7200 kg ha^{-1} and 4600 kg ha^{-1} for certain varieties in Peru and Mexico, respectively (Brenner et al., 2000).

Protein content

Experiment 2. The mean protein content of amaranth grain was 14.73% by variety and 14.51% across treatments (Table 10). Protein content was higher for the "golden" variety at 14.78% compared to "cream", which had a protein content of 14.62%.

Experiment 3. The mean protein content of amaranth grain was 14.73% by variety and 14.51% across treatments (Table 10). Protein content was higher for the "golden" variety at 15.47% than for "cream", which had protein content of 14.74%. Contrary to previous analyses performed on "cream" and "golden" varieties that reported values for protein content of 11.7% and 12.4% (Nakimbugwe, pers. comm.), respectively, the results from on-station experiments at Kabanyolo indicated that the protein content of these varieties was equivalent to what has been reported in the literature (Bressani, 1994). Based on observation, the "golden" variety had higher protein content than "cream", and values for protein content appeared higher during the rainy season than the dry season. Such a result is not expected, given that precipitation is generally the factor most limiting plant productivity in tropical agro-ecosystems. Further, precipitation generally increases plant availability of nitrogen and other nutrients in the soil, potentially leading to increased protein content (Sanchez, 1976; Elbehri et al., 1993). Possible explanations for differences in protein content reported by Nakimbugwe (2008) and those found in Kabanyolo will be discussed in Chapter 4, in combination with data from the on-farm trials.

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Figure 1. Latin Square experimental design and legend for on-station grain amaranth experiments, Kabanyolo, Uganda.

Row 1	Column 1	Block 1	1	2	3	4	5	6	7
			6	5	7	3	4	1	2
Row 1	Column 2	Block 2	8	9	10	11	12	13	14
			7	5	3	6	2	4	1
Row 1	Column 3	Block 3	15	16	17	18	19	20	21
			4	3	2	1	7	5	6
Row 2	Column 1	Block 4	22	23	24	25	26	27	28
			5	4	6	7	3	2	1
Row 2	Column 2	Block 5	29	30	31	32	33	34	35
			2	7	5	3	6	1	4
Row 2	Column 3	Block 6	36	37	38	39	40	41	42
			3	7	4	6	1	2	5
Row 3	Column 1	Block 7	43	44	45	46	47	48	49
			2	1	3	4	6	5	7
Row 3	Column 2	Block 8	50	51	52	53	54	55	56
			1	3	6	5	2	7	4
Row 3	Column 3	Block 9	57	58	59	60	61	62	63
			1	7	5	3	2	4	6

Legend

Varieties
Cream
Golden
Plainsman

Treatment	No.
Control	1
1 ton/ha compost	2
1.5 ton/ha compost	3
3 ton/ha compost	4
1 ton/ha manure	5
1.5 ton/ha manure	6
3 ton/ha manure	7

Table 1. Soil physical and chemical properties from on-station experimental site, Kabanyolo, Uganda

Sample no.	Depth	Quadrant	pH	SOM (%)	N (%)	P (mg kg^{-1})	K	Na	Ca	Mg	Ex. bases[1]	Sand	Clay	Silt
							------------- Cmoles$_c$ kg^{-1}------------					----------%---------		
1	0-15	SW	4.6	3.11	0.19	7.41	0.60	0.06	3.4	1.22	5.28	32	32	36
1	15-30	SW	3.8	1.04	0.10	4.35	0.51	0.05	2.1	0.69	3.35	54	24	22
2	0-15	SE	4.8	2.96	0.18	8.25	1.35	0.06	4.4	1.69	7.50	30	36	34
2	15-30	SE	4.0	1.12	0.12	4.15	0.78	0.05	3.1	1.22	5.15	44	38	18
3	0-15	NW	3.9	3.01	0.14	6.35	0.59	0.06	4.5	1.63	6.78	56	14	30
3	15-30	NW	3.6	1.05	0.10	3.22	0.42	0.05	2.0	0.96	3.43	44	38	18
4	0-15	NE	4.2	2.01	0.11	18.25	0.71	0.06	3.3	1.11	5.18	48	36	16
4	15-30	NE	3.8	1.02	0.10	3.26	0.29	0.08	1.2	0.65	2.22	36	48	16
Mean			4.1	1.92	0.13	6.91	0.66	0.06	3.0	1.15	4.86	43	33	24

[1]Exchangeable bases used as cation exchange capacity fails to account for H+ occupying exchange sites.

Table 2. Monthly precipitation and temperature, May to December 2009, Kabanyolo, Uganda.

	May			June			July			August		
Year	Max. temp. (°C)	Min. temp. (°C)	Precipitation (mm)	Max. temp. (°C)	Min. temp. (°C)	Precipitation (mm)	Max. temp. (°C)	Min. temp. (°C)	Precipitation (mm)	Max. temp. (°C)	Min. temp. (°C)	Precipitation (mm)
2009	27	17	55	27	17	82	23	16	87	27	17	169
Mean[1]	25	17	147	25	17	74	25	17	46	25	16	86

	September			October			November			December		
Year	Max. temp. (°C)	Min. temp. (°C)	Precipitation (mm)	Max. temp. (°C)	Min. temp. (°C)	Precipitation (mm)	Max. temp. (°C)	Min. temp. (°C)	Precipitation (mm)	Max. temp. (°C)	Min. temp. (°C)	Precipitation (mm)
2009	28	17	162	28	17	190	28	18	55	28	18	55
Mean[1]	27	17	91	27	17	97	27	17	122	27	17	99

[1] Mean values are those collected for Kampala, 18 km south of Kabanyolo.

Table 3. Mean percent germination of amaranth seedlings on 25 June 2009 and on 1 July 2009 from Experiment 1, by treatment and variety, Kabanyolo, Uganda.

	Germination (%)	
Treatment	25 June 2009	1 July 2009
Control	53.3a[1]	72.2a
1 ton ha^{-1} compost	48.3a	62.2a
1.5 ton ha^{-1} compost	56.7a	70.0a
3 ton ha^{-1} compost	54.4a	71.1a
1 ton ha^{-1} poultry manure	54.4a	68.9a
1.5 ton ha^{-1} poultry manure	54.4a	73.3a
3 ton ha^{-1} poultry manure	42.2a	63.3a
Variety		
Cream	55.7a	76.2a
Golden	68.1a	76.2a
Plainsman	32.1b	53.8a

[1]In each column, means followed by the same letter are not significantly different at P>0.05 (LSD test).

Table 4. Nutrient analysis of poultry manure and composted manure for on-station grain amaranth experiment, Kabanyolo, Uganda.

Sample	N (%)	P (mg kg^{-1})	K (Cmoles$_c$ kg^{-1})
Poultry manure	1.30	0.55	1.02
Composted manure	0.54	0.20	0.88

Table 5. Mean weed populations by treatment on 30 July 2009, 11 August 2009, and 22 August 2009, from Experiment 2, Kabanyolo, Uganda.

	Weed populations (number 0.09 m^{-2})		
Treatment	30 July 2009	11 August 2009	22 August 2009
Control	43.3a[1]	40.0a	78.0a
1 ton ha^{-1} compost	40.0a	90.0a	100.0a
1.5 ton ha^{-1} compost	63.3a	72.5a	72.0a
3 ton ha^{-1} compost	57.5a	50.0a	72.0a
1 ton ha^{-1} poultry manure	90.0a	43.3a	99.3a
1.5 ton ha^{-1} poultry manure	63.3a	52.5a	69.0a
3 ton ha^{-1} poultry manure	63.3a	70.0a	76.7a

[1]In each column, means followed by the same letter are not significantly different at P>0.05 (LSD test).

Table 6. Mean insect populations, by variety and treatment, on 27 August 2009 from Experiment 2, Kabanyolo, Uganda.

	27 August 2009
Treatment	Insect population (insects plant^{-1})
Control	3.3a
1 ton ha^{-1} compost	3.3a
1.5 ton ha^{-1} compost	2.3a
3 ton ha^{-1} compost	4.0a
1 ton ha^{-1} poultry manure	22.0a
1.5 ton ha^{-1} poultry manure	3.3a
3 ton ha^{-1} poultry manure	1.3a
Variety	
Cream	4.6a
Golden	6.8a

[1]In each column, means followed by the same letter are not significantly different at P>0.05 (LSD test).

Table 7. Mean plant height and leaf number on 4 September 2009 and 5 September 2009 for Experiment 2 by treatment and variety, Kabanyolo, Uganda.

Treatment	Plant height (cm)	Leaves (number plant^{-1})
	4 September 2009	5 September 2009
Control	100.4a[1]	103.2a
1 ton ha^{-1} compost	97.9a	96.1a
1.5 ton ha^{-1} compost	107.3a	80.9a
3 ton ha^{-1} compost	103.8a	91.6a
1 ton ha^{-1} poultry manure	97.9a	88.0a
1.5 ton ha^{-1} poultry manure	108.5a	75.4a
3 ton ha^{-1} poultry manure	103.9a	85.3a
Variety		
Cream	116.4a	50.8c
Golden	115.0a	79.4b
Plainsman	75.5b	138.8a

[1]In each column, means followed by the same letter are not significantly different at P>0.05 (LSD test).

Table 8. Mean amaranth grain yield, by variety and treatment, Experiment 2 and Experiment 3, Kabanyolo, Uganda.

	Experiment 2	Experiment 3
Treatment	Grain yield (kg ha^{-1})	Grain yield (kg ha^{-1})
Control	988.7a[1]	2336.5a
1 ton ha^{-1} compost	1097.0a	2191.2a
1.5 ton ha^{-1} compost	1108.1a	1921.9a
3 ton ha^{-1} compost	1105.9a	2471.5a
1 ton ha^{-1} poultry manure	1208.1a	1857.2a
1.5 ton ha^{-1} poultry manure	1116.7a	2701.2a
3 ton ha^{-1} poultry manure	1148.3a	2243.9a
Variety		
Cream	1013.1a	2750.2a
Golden	1207.7a	1742.3b
Plainsman	195.1b[2]	1165.6b

[1]In each column, means followed by the same letter are not significantly different at P>0.05 (LSD test).

[2]Data collected on ‘Plainsman’ variety was adjusted for statistical analysis due to low plant populations at harvest.

Table 9. Mean amaranth grain yield by row and column for Experiment 2 and Experiment 3, Kabanyolo, Uganda.

Blocking unit	Experiment 2 Grain yield (kg ha^{-1})	Experiment 3 Grain yield (kg ha^{-1})
Row 1	1043.9a[1]	2128.1a
Row 2	1189.6a	2356.6a
Row 3	1097.8a	2253.9a
Column 1	1109.6a	1708.6a
Column 2	1146.1a	2306.5ab
Column 3	1075.6a	2723.5b

[1]In each column, means followed by the same letter are not significantly different at P>0.05 (LSD test).

Table 10. Amaranth grain protein content, by variety and treatment, for Experiments 2 and 3, Kabanyolo, Uganda.

	Experiment 2	Experiment 3
Treatment	Protein content (%)	Protein content (%)
Control	14.31	15.12
1 ton ha^{-1}compost	14.22	14.99
1.5 ton ha^{-1}compost[1]		15.19
3 ton ha^{-1}compost	14.61	14.94
1 ton ha^{-1}poultry manure	14.49	15.01
1.5 ton ha^{-1}poultry manure	14.76	14.84
3 ton ha^{-1}poultry manure	14.66	15.34
Variety		
Cream	14.62	14.74
Golden	14.78	15.47
Plainsman[2]	14.78	

[1]Ground amaranth grain sample for the 1.5 ton ha^{-1}compost treatment rate for Experiment 2 was broken during shipping.

[2] Data collected on 'Plainsman' variety was excluded from analysis.

Table 11. Mean weed population count by treatment on 11 October 2009, 30 October 2009, and 14 November 2009 from Experiment 3, Kabanyolo, Uganda.

	Weed populations (number 0.09 m^{-2})		
Treatment	11 October 2009	30 October 2009	14 November 2009
Control	26.3a[1]	48.3a	58.3a
1 ton ha^{-1} compost	11.0a	13.3a	76.7a
1.5 ton ha^{-1}compost	12.7a	20.0a	53.3a
3 ton ha^{-1} compost	9.7a	48.3a	73.7a
1 ton ha^{-1} poultry manure	23.0a	53.3a	126.7a
1.5 ton ha^{-1} poultry manure	31.7a	56.7a	50.0a
3 ton ha^{-1} poultry manure	15.0a	65.0a	46.3a

[1]In each column, means followed by the same letter are not significantly different at P>0.05 (LSD test).

Table 12. Mean weed population count by row and column on 11 October 2009, 30 October 2009, and 14 November 2009 from Experiment 3, Kabanyolo, Uganda.

	Weed populations (number 0.09 m^{-2})		
Blocking unit	11 October 2009	30 October 2009	14 November 2009
Row 1	19.1a[1]	37.9a	82.7a
Row 2	19.6a	31.4a	70.0a
Row 3	16.7a	61.4a	55.1a
Column 1	25.9a	51.9a	76.4a
Column 2	12.8a	30.6a	72.5a
Column 3	17.5a	51.0a	56.7a

[1]In each column, means followed by the same letter are not significantly different at P>0.05 (LSD test).

Table 13. Mean insect population count by variety and treatment on 6 November 2009, 14 November 2009, and 29 November 2009 for Experiment 3, Kabanyolo, Uganda.

	Insect population (insects plant $^{-1}$)		
Treatment	6 November 2009	14 November 2009	29 November 2009
Control	21.0a[1]	33.3a	104.0a
1 ton ha^{-1} compost	13.5a	20.3a	44.5a
1.5 ton ha^{-1} compost	5.0a	48.7a	66.7a
3 ton ha^{-1} compost	12.0a	50.0a	43.3a
1 ton ha^{-1} poultry manure	12.3a	33.8a	66.7a
1.5 ton ha^{-1}poultry manure	20.0a	13.7a	30.7a
3 ton ha^{-1} poultry manure	23.3a	35.0a	60.0a
Variety			
Cream	6.0a	36.8a	57.4a
Golden	19.0a	40.1a	64.0a
Plainsman[2]	19.9a	17.7a	48.3a

[1]In each column, means followed by the same letter are not significantly different at P>0.05 (LSD test).

[2]Data collected on ‘Plainsman’ variety was excluded from analysis.

Table 14. Mean insect population count by row and column on 6 November 2009, 14 November 2009, and 29 November 2009 for Experiment 3, Kabanyolo, Uganda.

	Insect population (insects plant $^{-1}$)		
Blocking unit	6 November 2009	14 November 2009	29 November 2009
Row 1	21.7a[1]	31.4a	40.7a
Row 2	10.7a	37.1a	51.0a
Row 3	12.4a	28.5a	78.0a
Column 1	16.8a	15.0a	77.3a
Column 2	10.1a	33.2a	58.9a
Column 3	17.6a	38.9a	46.7a

[1]In each column, means followed by the same letter are not significantly different at P>0.05 (LSD test).

Table 15. Mean plant height measurement by variety and treatment on 6 November 2009, 21 November 2009, and 28 November 2009 from Experiment 3, Kabanyolo, Uganda.

	Plant height (cm)		
Treatment	6 November 2009	21 November 2009	28 November 2009
Control	56.1a[1]	88.2a	111.1a
1 ton ha^{-1} compost	58.2a	95.1a	107.3a
1.5 ton ha^{-1} compost	56.7a	86.2a	104.1a
3 ton ha^{-1} compost	60.1a	97.3a	110.6a
1 ton ha^{-1} poultry manure	59.1a	96.7a	112.8a
1.5 ton ha^{-1} poultry manure	56.5a	97.9a	117.7a
3 ton ha^{-1} poultry manure	55.1a	86.7a	104.5a
Variety			
Cream	44.2b	82.7	110.7ab
Golden	68.9a	109.5	125.8a
Plainsman	59.1a	85.6	92.7b

[1]In each column, means followed by the same letter are not significantly different at P>0.05 (LSD test).

Table 16. Mean plant leaf numbers by variety and treatment on 28 November 2009 from Experiment 3, Kabanyolo, Uganda.

	Leaves (number plant^{-1})
Treatment	28 November 2009
Control	103.2a[1]
1 ton ha^{-1} compost	101.2a
1.5 ton ha^{-1} compost	105.0a
3 ton ha^{-1} compost	97.6a
1 ton ha^{-1} poultry manure	96.0a
1.5 ton ha^{-1} poultry manure	98.0a
3 ton ha^{-1} poultry manure	96.0a
Variety	
Cream	72.8b
Golden	90.6b
Plainsman	135.4a

[1]In each column, means followed by the same letter are not significantly different at P>0.05 (LSD test).

CHAPTER 4: ORGANIC AMARANTH ON-FARM EXPERIMENTS IN UGANDA

Introduction: Project Overview

On-farm trials in Kamuli District of eastern Uganda were initiated in late August 2009 to complement the on-station trials in Kabanyolo, Uganda (Chapter 3). Although the experiments had a similar design as the on-station trials, the on-farm trials were smaller in scope, and were based more specifically on information obtained through informal surveying of VEDCO contact farms in the Kamuli District in June 2009. That survey indicated that farms in the area were growing both “cream” and “golden” varieties and that, where employed, cattle manure was the most common organic soil amendment applied to grain amaranth crops. As such, the farmer-managed experiments were designed to match farmer conditions to determine the effects of organic soil amendments on amaranth grain yield and protein content for locally-grown amaranth varieties.

Materials and Methods

Site characteristics

The study was conducted in Kamuli District of Uganda, located in the forest-savannah mosaic zone between 0^0 56' – 1^0 20' N latitude and 33^0 .05' – 33^0 .20' E longitude. The altitude averages 1,082 m above sea level and precipitation has a bimodal distribution with an annual total of 135 cm (Sseguya et al., 2009). The length and severity of the dry season have been increasing in recent years (Kizza et al., 2009). The farming systems of the area lie on a precipitation-determined gradient, displaying characteristics of both the maize-mixed systems typical in Southern and East Africa, as well as those of the highland perennial system more common in south-central Uganda and Rwanda (Hall et al., 2001). Soils in the study area were predominantly sandy clay loams that exhibit good physical properties but are deficient in major plant nutrients (NARO, 2009).

Research design

Farms in the study area were “contact farms” working in conjunction with VEDCO, the local NGO associated with CSRL efforts. Their farms were concentrated in six parishes in the western part of Kamuli District in the vicinity of Kamuli Town. Farms were recruited prior to the beginning of the short rainy season in the area (September-November) through individual on-farm visits, where I communicated the nature and goals of the experiment through a VEDCO translator. A total of eleven individual farms from six parishes agreed to participate in the on-farm trials. The six parishes, by number of participants, included Butansi (3), Nawanende (2), Naluwoli (2), Kasambira (2), Kasozi (1), and Namasagali (1). The approximate latitude, longitude, and elevation of each of the foregoing parishes was as follows: Butansi – 0°54'59.48"N latitude, 33° 5'36.53"E longitude, 1075 m elevation; Nawanende – 0°48'0.80"N latitude, 33°11'49.55"E longitude, 1110 m elevation; Naluwoli – 0°58'26.27"N latitude, 33° 3'28.99"E longitude, 1075 m elevation; Kasambira – 0°47'41.39"N latitude, 33° 7'35.59"E longitude, 1055 m elevation; Kasozi – 1° 4'23.84"N latitude, 33° 0'25.99"E longitude, 1060 m elevation; Namasagali – 1° 0'52.12"N latitude, 32°56'54.13"E longitude, 1040 m elevation. However, as discussed below, only ten of these farms were ultimately included in the analysis. Participating farms were subsequently assigned random numbers for identification to ensure confidentiality of results.

Since recruited farms were already planning to grow amaranth during the rainy season, all farms had selected in advance fields in which amaranth was to be planted.

Therefore, experimental plots were simply incorporated into the farms' pre-selected amaranth fields.

The experimental design was based on the results of the amaranth survey discussed in Chapter 2. Particularly, survey results indicated that cattle manure was the most frequently used and widely available organic soil amendment used by farms in Kamuli, while "cream" and "golden" amaranth were the only varieties in production. As such, the experimental design for individual fields followed a Randomized Complete Block (RCB) design by treatment, with treatments consisting of two rates of organic soil amendments and two amaranth varieties, "cream" and "golden," giving a total of four individual experimental plots per farm. Soil amendment treatments consisted of no soil amendments (control plots) and cattle manure applied at a rate of 27.1 ton ha^{-1}. The total area of individual plots was $5.5m^2$ (4ft x 15ft, or $60ft^2$) for eight of the farms, while one farmer maintained a planted area of $7.4m^2$ (4ft x 20 ft, 80 ft^2). One of the original eleven farms, Farm No. 5 from Butansi parish, deviated from the foregoing protocols by applying cattle manure at a decreased rate of 16.9 ton ha^{-1} and used a plot size of 2.4m x 4.9m, or $11.9m^2$ (8ft x 16ft, or $128ft^2$). Results from this farm were therefore excluded from the statistical analysis, but are included in the general discussion of the on-farm trials for comparative purposes.

For planting material, seed was collected from four individual farms participating in the experiment and subsequently pooled and distributed to the group as a whole. Cattle manure was obtained from each individual farmer's homestead.

Data collection

The experiment was overseen and implemented by Ms. Mercy Kabahuma, an undergraduate student at Makerere University and VEDCO employee. Soil samples from the center of each individual field to be planted in grain amaranth were sampled to a depth of 15 cm using a hand auger and transferred to the Soil Science Laboratory at Makerere University (Kampala, Uganda) for analysis. Soils were analyzed for pH, soil organic matter (SOM), total N, available P, exchanges bases of sodium (Na), potassium (K), magnesium (Mg), and calcium (Ca), and texture using standard procedures described in Okalebo et al. (1993). Daily precipitation and temperature for Kamuli were not available for the time period under study.

For each farmer, planting date was based on individual preference and was recorded. Farms were monitored throughout the course of the experiment and each farmer was visited six times (not including harvest) for data collection purposes throughout the course of the growing season, with the exception of Farm No. 4, who was visited five times.

Data was collected on date(s) of weeding and date(s) of thinning through informal surveying of farms. Data on plant height were obtained during each farmer visit on all farms, while qualitative assessments of weather, data on percentage of healthy plants, plants with damaged leaves (by insects), and percentage of diseased plants was recorded for all but the last farmer visit/monitoring. Due to logistical constraints, all farms could not be visited on the same day for data collection purposes, but the time between farm visits was approximately two weeks.

Plant height data was collected by measuring all plants in each individual plot from the base to the apex of the plant. Data collection on the percentage of plants with damaged leaves was conducted by visually assessing all plants in each individual plot for leaf damage.

It was assumed that observations would be statistically valid, based on the uniform visual assessments of one observer across all treatment groups on all farms. A similar logic was applied in analyzing the percentage of healthy plants and the percentage of diseased plants, which were tabulated by observing all plants in each plot and making qualitative assessments as to whether plants were "healthy" or "diseased."

Qualitative assessments of weather were obtained through an informal survey of each farmer to assess if weather had been "bad", "good", "excellent", or "thunderstorms." "Bad" weather portended less than three days of rain in the two days prior to the farm visit/monitoring; "good" weather indicated seven rainy days in the previous two weeks; "excellent" weather indicated precipitation on nearly all days during the previous two weeks; "thunderstorms" indicated that strong winds and rains had predominated during the previous two weeks.

Harvest date also varied between farms and was recorded for each site. Plant height and plant density, determined by counting the number of plants per individual plot, were recorded at harvest for each individual farmer. All farms, were instructed as to appropriate harvesting methods, and conducted harvesting independently. Harvesting of amaranth grain was conducted by cutting off seed heads for all plants from each individual plot, with seed heads subsequently dried in the sun on tarpaulin or on cloth (if the former was unavailable), for an average of three days across all farms. Subsequently, seed heads were threshed and winnowed using methods described in Chapter 3. Amaranth grain from each individual plot was kept separately and transported to Makerere University to be weighed independently by Ms. Kabahuma using an electronic balance.

For analysis of amaranth grain protein content, amaranth grain from individual plots was ground into flour and kept under refrigeration at Makerere University until 26 January 2010. Ground samples were then conveyed by air from Uganda and to Iowa State University in Ames, Iowa, USA. A sample of 10g of ground amaranth grain from each individual plot for all farms was then shipped to the laboratories of AIB International, Inc. (Manhattan, KS) and analyzed for protein content.

Data analysis

Plant height, yields and protein content were analyzed using JMP Statistical Software (Cary, NC) with Standard Least Squares personality and restricted maximum likelihood (REML) method to account for the complexity of the RCB split-plot design. Standard Least Squares personality and restricted maximum likelihood (REML) was also used to assess farmer, treatment, and variety differences for qualitative parameters related to plant health: percentage of healthy plants, percentage of diseased plants, and percentage of plants with damaged leaves (presumably by insect pests). Model effects included farmer number, variety, treatment, and their interactions, while a random component was assigned to the interaction between farmer number and treatment to account for the RCB design. Yields were log-transformed from kilograms per hectare to control for variance in the data. Regression analysis was used to determine statistical relationships for all other parameters not included in the model.

Results and Discussion

Farm demography

The ten farms who participated and met data analysis criteria resided in the three sub-counties of Bugulumbya (4), Namasagali (2), and Butansi (4) (Table 1). This distribution is fairly representative of the 34 farms originally surveyed on practices and issues associated with grain amaranth (Chapter 2), where the breakdown by sub-county was similar, with most farms surveyed in Bugulumbya (47%) and Butansi (35%), but fewer in Namasagali (18%). Similarly, farmer location by parish, as a percentage of surveyed farms, was Butansi (27%), Kasambira (18%), Kasozi (9%), Naluwoli (18%), Namasagali (9%), and Nawanende (18%).

Of the original eleven farmer participants, nine were women and two were men. The ratio of women to men for the on-farm trials was therefore slightly higher than for the surveyed farms, where 72% of correspondents were women. The mean age of on-farm trial participants was 44 years with a standard deviation of 8.9 years, and was similar to that found in the survey, where the mean age was 43 with a standard deviation of 11 years. The minimum age of participants in the on-farm trials was 30 years, identical to that of the farmer survey, while the maximum age of trial participants (64 years) was lower than the maximum of 75 years in the survey.

Soils

Surface soils on the participating farms were primarily sandy clay loams (seven farms) with some sandy loams (three farms) and were probably Oxisols, based on previous surveys. As such, soil fine earth fraction values were relatively high for sand and clay, but lower for silt. Average sand content for all samples was 64% (Table 1). Sand content was highest for Farms No. 6 and 10, where the soils were 72% sand. Farm No. 2 had the least sandy soils, with a value of 52% sand. Clay content ranged from a high of 30% for Farm No.

2, to a low of 18% for Farms No. 4 and 10; average clay content was 22% for all samples. The highest silt content was recorded at 22% for Farm No. 4, while the lowest occurred for Farm No. 8, where silt content was 16%. Mean silt content for all samples was 14%.

The soil fine earth fraction among on-trial farms was similar to the on-station site, where means were 62% clay, 23% clay, and 15% silt, with concomitant standard deviations of 9%, 7%, and 4%. Mean values for the Namulonge survey were 52% sand, 34% clay and 14% silt, with respective standard deviations of 5%, 5%, and 4%.

Soils were moderately acidic, with an average pH of 5.7 across all soil samples (Table 1). The highest pH value of 6.4 was recorded for Farms No. 3 and 11. The lowest pH of 4.9 was recorded for Farm No. 1. The pH values were similar to the 33 soil samples collected from farms associated with the aforementioned survey on amaranth practices and issues (Chapter 2, Tables 1-4), as mean pH across all farms (inclusive of the 11 farms participating in the on-farm trials) was 5.5 with a standard deviation of 0.7. However, these values were lower than those reported for 60 farms in Kamuli District associated with the Namulonge Bean Programme, which maintained pH values of 6.0 to 7.2 (NARO, 2009).

Soil organic matter (SOM) was fairly low among participants, with a mean value of 2.48% across all samples. Of the eleven farms participating in the study, three had SOM levels above 3.0%. The SOM was highest for Farm No. 9, with a value of 3.68% SOM. The lowest recorded value for soil organic matter was 1.65% for Farm No. 8. Soil nitrogen was measured as Total Nitrogen (TN) and maintained a mean of 0.14% N across all samples. The highest N value was recorded as 0.20% in two instances for Farms No. 5 and 9. The lowest value was 0.09% N and was recorded for Farm No. 3.

These values were similar to the farmer survey, where the recorded mean was 2.46% SOM with a standard deviation of 0.88%. However, values for SOM were lower compared to the Namulonge Bean Programme data, where the mean across 60 farms was 3.2% SOM with a standard deviation of 0.4%. The mean value for nitrogen among amaranth survey farms was 0.13% N with a standard deviation of 0.04%. For the Namulonge survey, the mean across 60 farms was 0.19% N, while the standard deviation was 0.02%.

Average phosphorus values were low overall and averaged 13.2 mg kg^{-1} P. The highest P value was recorded at 38.1 mg kg^{-1} P for Farm No. 2, while the lowest P value recorded was 5.57 mg kg^{-1} for Farm No. 3. These numbers were in line with average values obtained in the amaranth survey, which found a mean phosphorus content of 8.57 mg kg^{-1} P and a standard deviation of 6.14 mg kg^{-1} P. The Namulonge survey reported lower soil P numbers than those demonstrated here, as 56 of 60 surveyed farms had soil P below the minimal reporting standard of 5.00 mg kg^{-1} P.

Values for the four major soil cations, potassium, sodium, calcium, and magnesium, were also low. Potassium ranged from 2.72 $Cmoles_c$ kg^{-1} K for Farm No. 1 to a low of 0.36 $Cmoles_c$ kg^{-1}K for Farm No. 4, with a mean for all samples of 1.07 $Cmoles_c$ kg^{-1} K. Sodium ranged from a maximum of 0.11 $Cmoles_c$ kg^{-1} Na for Farm No. 9 to a minimum 0.04 $Cmoles_c$ kg^{-1} Na for Farms No. 5 and 10; the mean sodium value for samples was 0.08 $Cmoles_c$ kg^{-1} Na. Calcium values ranged from a high of 6.7 $Cmoles_c$ kg^{-1} Ca for Farm No. 5 to a low of 3.4 $Cmoles_c$ kg^{-1} Ca for Farm No. 3; the mean calcium value for all samples was 4.3 $Cmoles_c$ kg^{-1} Ca. The highest recorded value for magnesium was 2.18 $Cmoles_c$ kg^{-1}Mg for Farm No. 5, while the lowest 1.00 $Cmoles_c$ kg^{-1} Mg for Farm No. 2. The mean recorded magnesium value was 1.47 $Cmoles_c$ kg^{-1} Mg. Tabulating the foregoing cation values provides maximum exchangeable bases as 9.8 $Cmoles_c$ kg^{-1} for Farm No. 5, and minimum of 5.8 $Cmoles_c$ kg^{-1} for Farm No. 6. Mean exchangeable bases for all samples was 6.92 $Cmoles_c$ kg^{-1}.

Soil cation values for farms in on the farm trials were slightly higher than those found via the amaranth survey for K, where the mean was 0.92 $Cmoles_c$ kg^{-1} K and standard deviation of 0.71 $Cmoles_c$ kg^{-1} K. Similarly, the Namulonge survey reported mean values of 1.14 $Cmoles_c$ kg^{-1} K, 7.29 $Cmoles_c$ kg^{-1} Ca, and 4.13 $Cmoles_c$ kg^{-1} Mg, with respective standard deviations of .57 $Cmoles_c$ kg^{-1} K, 2.42 $Cmoles_c$ kg^{-1} Ca, and 0.79 $Cmoles_c$ kg^{-1} Mg.

As discussed in Chapter 3, the foregoing values indicate the possibility of systemic differences related to soil sampling. These factors include differences in sampling depth for Namulonge and those reported here, differences in analytical methods between laboratories, and differences between farms' fields related to specific crop history.

No significant regressions were determined for soil physical and chemical properties against yield. Regression analysis indicted the following P values: SOM (P=0.7105), P (P=0.6021), Na (P=0.5367), Mg (P=0.6678), and sand content (P=0.3048), pH (P=0.1917), N (P=0.8530), K (P=0.4974), exchangeable bases (P=0.7144), and silt content (P=0.2129). The yield trend for Ca (P=0.9964) and clay content (P=0.9301) was close to neutral.

Precipitation and temperature

Daily precipitation for the entire period of the study was unobtainable due to lack of operational weather stations in the area. However, informal and scientific studies corroborated a trend of increasing precipitation variability and lengthening of the dry season associated with the ENSO phenomena for Kamuli and the Lake Victoria littoral area (Kizza et al., 2009; Phillips and McIntyre, 2000; Sseguya et al., 2009). Indeed, the onset of precipitation associated with the long rainy season in Kamuli was delayed by more than a month from the norm in 2009, according to local sources.

Planting and harvest date

Planting date varied between farms and between treatments (data not presented). The median planting date was 3 September 2009. The earliest planting date was for Farm No. 2, who planted both "cream" and "golden" varieties with the cattle manure treatment on 28 August 2009. Farm No. 6 had the latest planting date and planted both treatments and varieties on 15 September 2009. Farm No. 1 planted both varieties for the control treatment on the median date.

Amaranth harvest dates ranged from 4 November 2009 at the earliest for "golden" variety by Farm No. 9, to 10 December 2009 for Farm No. 7's "cream" variety (data not presented). The 25 November 2009 harvest date represented the median harvest date, with Farms No. 1 and 3 harvesting all treatments and varieties on this date.

Aggregating these two data points provided information on days to harvest, which served as a covariate for days to maturity (data not presented). Mean days to harvest across all farms was 76.3 days, with a standard deviation of 6.5 days. The maximum days to harvest was 93 days, recorded for the "cream" variety planted by Farm No. 7, while the minimum days to harvest was 57 days for the "golden" variety of Farm No. 9. Simple ANOVA analysis indicated no significant differences between harvest dates by treatment (P=0.8838), but recorded significant differences at $P \leq 0.10$ for variety, with "cream" having longer days to harvest (78.7d) than "golden" (75.0d) (P=0.0844).

The mean days-to-harvest parameter for the on-farm experiments was lower than for the on-station trials, where days to harvest ranged from 80 to 98 DAP, depending on variety. This difference may correspond to individual farmer strategies related to risk and time management, where participants may have harvested earlier to mitigate degradation or loss of grains from pest damage or theft. Further, amaranth grain typically reaches maturity quickly relative to other crops, and participants may have harvested amaranth grains in advance of later-maturing crops for this reason. No significant relationship was detected between yields and days to harvest, however (P=0.3796).

Regression analysis indicated a positive relationship between yield and planting date (i.e., later planting dates) (P=0.0557), but not for harvest date (P=0.8373) or days to harvest (P=0.5471). The opposite trend was exhibited for protein content, with a significant negative regression analysis for protein and later planting dates (P=0.0038), but no relationship was determined between protein and harvest date (P=0.2019) or days to harvest (P=0.9534). Also of interest was the relationship between planting date and planting density, where there was a significantly negative regression between planting date and planting density (P=0.0001).

Weeding and thinning

Weeding of amaranth plants was conducted on average, across all farms, treatments and varieties, 2.8 times during the growing season, with eight of ten farms weeding three times and the remainder weeding twice (data not presented). Time intervals for weeding operations indicated that the first weeding was conducted, on average, 17.6 days after planting with a standard deviation of 5.2 days. The mean days after planting for the second weeding was 38.7 days, while the standard deviation was 9.1 days. Across farms who conducted weeding operations three times, the mean days after planting for the third weeding session was 50.8 days with a standard deviation of 4.4 days.

Most farms practiced thinning to permit greater spacing between amaranth plants to facilitate greater production. On average, plants were thinned 2.7 times during the growing season. Most farms conducted weeding and thinning operations simultaneously. As such, the mean date for initial thinning was 18.4 days with a standard deviation of 6.8 days. The average days after planting date for the second thinning was identical to the mean for the second weeding, taking place 38.7 days after planting with a standard deviation of 9.1 days. This pattern was repeated for the third thinning.

Planting density

Mean planting density across all farms, treatments and varieties was 11.2 plants m^{-2}, with a standard deviation of 7.6 plants m^{-2} (data not presented). The maximum planting density was 36.4 plants m^{-2} for Farm No. 8's "cream" variety with cattle manure treatment, while the minimum was 4.2 plants m^{-2} for the "golden" variety of Farm No. 11 in the control treatment.

Mean planting density, according to one-way ANOVA, was significantly different between farms (P=0.0001), but not between varieties (P=0.4710) or treatments (P=0.7864). Comparison of means using Tukey HSD also indicated significant differences in planting density between farms. Regression analysis of planting density against yield displayed a negative trend, but not a significantly negative relationship between the two parameters

(*P*=0.2417). However, there was a significantly positive regression between planting density and protein content (*P*=0.0078).

Regression analysis demonstrated no significant relationship between number of weedings and yield (*P*=0.5640); however, there was a significantly negative relationship (at the $P \leq 0.10$ confidence level) between later weeding dates, relative to planting date, and yield for both the second (*P*=0.0918) and third weeding sessions (*P*=0.0027). Number of thinning sessions, however, did not affect yield (*P*=0.8799), but there was a significantly negative relationship between yield and relative thinning date (at the $P \leq 0.10$ confidence level) for both the first and second thinning (*P*=0.0565, *P*=0.0918).

By contrast, regression analysis of protein content against relative weeding and thinning dates demonstrated the opposite trend, with protein content tending to decrease, though not significantly, for both number of weedings (*P*=0.5855) and thinnings (*P*=0.4056). There was a significantly positive relationship (at the $P \leq 0.10$ confidence level) between later relative weeding dates for the second weeding (*P*=0.0657) and for the third weeding (*P*=0.0041).

Plant height

Amaranth plant height was significantly different between farms at the first farm visit (*P*=0.0290), but not between treatments (*P*=0.1249) or varieties (*P*=0.9976) (Table 2). There was no significant interaction between treatment and variety (*P*=0.8845), or between variety and farm (*P*=0.8406). Plant height averaged 13.3 cm in the cattle manure treatment and 9.9 cm in the control. Plant height in the “cream” and “golden” varieties was identical, averaging 11.6 cm (Table 2).

On the second farm visit, plant height was significantly different between treatments (*P*=0.0442), but not between farms (*P*=0.1338) or varieties (*P*=0.1627) (Table 2). There was no significant interaction between treatment and variety (*P*=0.7646), or between variety and farmer (*P*=0.4588). Mean plant height was 41.8 cm in the cattle manure treatment and 30.2 cm in the control. Mean plant height for "cream" was 34.0 cm, while "golden" was 38.0 cm.

On the third farm visit, plant height was significantly different between treatments (*P*=0.0285), but not between farms (*P*=0.1891) or varieties (*P*=0.7389) (Table 2). There was no significant interaction between treatment and variety (*P*=0.5626), or between variety and farm (*P*=0.3542). By treatment, mean plant height was 86.9 cm in the cattle manure treatment and 62.7 cm in the control. Mean plant height for "cream" was 69.1 cm, while "golden" was 71.7 cm.

On the fourth farm visit, plant height was significantly different between treatments (*P*=0.0310), but not between farms (*P*=0.1023) or varieties (*P*=0.1473) (Table 3). There was no significant interaction between treatment and variety (*P*=0.1566), or between variety and farm (*P*=0.4936). By treatment, mean plant height was 133.7 cm in the cattle manure treatment and 101.9 cm in the control. Mean plant height for "cream" was 122.4 cm, while "golden" was 113.2 cm.

On the fifth farm visit, plant height was significantly different between treatments (*P*=0.0256) and varieties (*P*=0.0366), but not between farms (*P*=0.1189) (Table 3). There was no significant interaction between treatment and variety (*P*=0.1775), or between variety and farm (*P*=0.3463). By treatment, mean plant height was 163.7 cm in the cattle manure treatment and 127.5 in for the control. Mean plant height for "cream" was 154.8 cm, while "golden" was 136.4 cm.

On the sixth farm visit, plant height was significantly different between treatments (*P*=0.0464) and varieties (*P*=0.0200), but not between farms (*P*=0.1255) (Table 3). There was no significant interaction between treatment and variety (*P*=0.1816), or between variety and farm (*P*=0.3942). By treatment, mean plant height was 180.4 cm in the cattle manure treatment and 143.0 cm in the control. Mean plant height for "cream" was 169.1 cm, while "golden" was 143.5 cm.

Plant height at harvest was significantly different between treatments (*P*=0.0437), varieties (*P*=0.0005), and farms (*P*=0.0288) (Table 3). There was no significant interaction between treatment and variety (*P*=0.6323), or between variety and farm (*P*=0.0858). By treatment, mean plant height was 175.5 cm in the cattle manure treatment and 151.0 cm in the control. Mean plant height for "cream" was 179.0 cm, while "golden" was 147.5 cm.

Regression analysis indicated that plant height represented a positive regressor for amaranth grain yield (log-transformed), as there was a positive regression between plant height at each farm visit, representing plant growth over time, and yield. Plant height was a significant regressor for yield at the first farm visit (*P*=0.0003) and at harvest (*P*=0.0072). Plant height was a significantly negative regressor for protein content at the first farm visit (*P*=0.0001), but this relationship subsequently disappeared and there was a trend towards a positive relationship at the time of plant harvest (*P*=0.3167).

Plant health

At the first farm visit, the percentage of healthy plants was significantly different between treatments (*P*=0.0385), but not between farms (*P*=0.1625) or varieties (*P*=0.6768) (Table 4). There was no significant interaction between treatment and variety (*P*=0.8342), or between variety and farm (*P*=0.1250). The average percentage of healthy plants was 94.3% in the cattle manure treatment and 74.8% in the control. Percentage of healthy plants for the "cream" variety was 84.0%, while "golden" was 85%. At the second farm visit, the percentage of healthy plants was again significantly different between treatments (*P*=0.0319), but not between farms (*P*=0.1232) or varieties (*P*=0.9313) (Table 4). Mean percentage of healthy plants was 96.5% in the cattle manure treatment and 86.8% in the control. There was no significant interaction between treatment and variety (*P*=0.6680), or between variety and farm (*P*=0.1179). Percentage of healthy plants for "cream" was 91.5%, while "golden" was 91.8%. At the third farm visit, the percentage of healthy plants was also significantly different between treatments (*P*=0.0029), but not between farms (*P*=0.2211) or varieties (*P*=0.8511) (Table 4). Mean percentage of healthy plants was 97.5% in the cattle manure treatment and 84.0% in the control. There was no significant interaction between treatment and variety (*P*=0.5763), or between variety and farm (*P*=0.0917). Percentage of healthy plants for "cream" was 90.5%, while "golden" was 91.0%.

At the fourth farm visit, the percentage of healthy plants was again significantly different between treatments (*P*=0.0010), but not between farms (*P*=0.1852) or varieties (*P*=0.6084) (Table 5). Mean percentage of healthy plants was 94.0% in the cattle manure treatment and 79.0% in the control. There was no significant interaction between treatment and variety (*P*=0.3160), or between variety and farm (*P*=0.1811). Percentage of healthy plants for "cream" was 87.5%, while "golden" was 85.5%. On the fifth farm visit, the percentage of healthy plants was also significantly different between treatments (*P*=0.0102), but not between farms (*P*=0.5371) or varieties (*P*=0.2054) (Table 5). There was no significant interaction between treatment and variety (*P*=0.0942), or between variety and farm (*P*=0.2196). Mean percentage of healthy plants was 94.0% in the cattle manure treatment and 79.0% in the control. Percentage of healthy plants for “cream” was 87.5%, while “golden” was 85.5%.

Regression analysis of healthy plants against log-transformed amaranth grain yields indicated a positive relationship between plant health and yields for all sampling intervals except the first farm visit (*P*=0.9160). This trend was particularly strong when correlated with the second farm visit (*P*=0.0431) and the fifth farm visit (*P*=0.0227). However, there was no significant regression observed between plant health assessments and protein content.

Damaged plants

The percentage of plants with damaged leaves at the first farm visit indicated a significant difference between varieties (*P*=0.0484), but not between treatments (*P*=0.9635) or farms (*P*=0.1789) (Table 8). There was significant interaction between variety and farm (*P*=0.0099), but not between treatment and variety (*P*=0.2042). Mean percentage of plants with damaged leaves was 19.8% in the cattle manure treatment and 20.0% in the control. Percentage of plants with damaged leaves for “cream” was 18.0%, while “golden” was 21.8%. Percentage of plants with damaged leaves for the second farm visit was not significantly different between varieties (*P*=0.1279), treatments (*P*=0.9212), or farms (*P*=0.1282) (Table 8). There was no significant interaction between treatment and variety (*P*=0.6337), or between variety and farm (*P*=0.0657). Mean percentage of plants with damaged leaves was 36.5% in the cattle manure treatment and 35.8% in the control. Percentage of plants with damaged leaves for “cream” was 34.0%, while “golden” was 38.3%.

Percentage of plants with damaged leaves for the third farm visit was significantly different between farms (*P*=0.0225) and varieties (*P*=0.0022), but not between treatments (*P*=0.3842) (Table 8). There was significant interaction between variety and farm (*P*=0.0217), but not between treatment and variety (*P*=0.1969). Mean percentage of plants with damaged leaves was 36.5% in the cattle manure treatment and 35.8% in the control. Percentage of plants with damaged leaves for “cream” was 34.0%, while “golden” was 38.3%.

Percentage of plants with damaged leaves for the fourth farm visit was significantly different between varieties (*P*=0.0052), but not between treatments (*P*=0.9635) or farms (*P*=0.0649) (Table 9). There was no significant interaction between variety and farm (*P*=0.1192) or between treatment and variety (*P*=0.6617). Mean percentage of plants with damaged leaves was 57.5% in the cattle manure treatment and 67.0% in the control. Percentage of plants with damaged leaves for “cream” was 56.0%, while “golden” was 68.5%. Percentage of plants with damaged leaves for the fifth farm visit was significantly different between varieties (*P*=0.0024), but not between treatments (*P*=0.1309) or farms (*P*=0.2167) (Table 9). There was no significant interaction between variety and farm (*P*=0.1367) or between treatment and variety (*P*=0.9899). Mean percentage of plants with damaged leaves was 65.0% in the cattle manure treatment and 74.9% in the control. Percentage of plants with damaged leaves for “cream” was 62.0%, while “golden” was 77.9%.

Regression analysis found no significant relationship between the percentage of damaged plants and amaranth grain yields across all farm visits. Regarding protein content, the relationship of percentage of damaged leaves to yield was negative (at the $P \leq 0.10$

confidence level) for the first farm visit (P=0.10 20), but no significant relationship was determined for later farm visits.

Diseased plants

The percentage of diseased plants was not significantly different for any of the model effects across all farm visits (Tables 6-7). However, there were some notable trends, especially for treatment and treatment by variety interaction, where both were significant (at the $P \leq 0.10$ confidence level) for the fourth and fifth farm visits (treatment effects: P=0.0811 and P=0.0629 for the fourth and fifth farm visits, respectively; treatment by variety interaction effects: P=0.0522 and P=0.0510, for the fourth and fifth farm visits, respectively). By treatment, prevalence of diseased plants was higher in control treatments compared to the cattle manure treatment, with the exception of the first farm visit, where there were no diseased plants on any farm. The “cream” variety exhibited a trend towards a higher percentage of diseased plants across farm visits; however, this difference was not significant (P=0.6506 for the second farm visit; P=0.1679 for the fifth farm visit). Regression analysis indicated no significant relationship between plant disease assessments and amaranth grain yields and protein content.

Weather assessment

Qualitative weather assessments illustrated no consistent relationship with any plant health, growth or yield parameters. Weather variability reported during these experiments, however, particularly regarding precipitation differences, most probably affected growth and yields.

Yields

Variability among farms. Analysis of log-transformed amaranth grain yields indicated significant differences in yield between farms (P=0.0259) (Table 10). However, this outcome was dependent upon the inclusion of a statistic from the "cream" variety treated with cattle manure on Farm No. 6, which yielded 2185.8 kg ha^{-1} (7.69 kg ha^{-1} in log form). When this data point is excluded, yields between farms are not significantly different at the $P\leq0.05$ confidence level (P=0.0523). If we incorporate the aforementioned data point, Farm No. 6 obtained the highest average yields, at 1229.5 kg ha^{-1}. Farm No. 11 had the lowest average yields at 239.1 kg ha^{-1}.

Qualitative weather assessments discussed above, as well as those outlined in Chapter 3, indicated variability in weather conditions between farms, and within the Kamuli District, as a whole during this study period. Thus, variation in precipitation was a possible cause for yield differences between farms, with farms receiving higher precipitation most probably obtaining higher yields, although quantitative weather data cannot be used to prove this statement.

Regarding the effect of soils on yields, as discussed in Chapter 2, statistical analysis of soils within the 33 farms in the survey indicated no significant differences in soil physical and chemical properties between sub-counties and parishes, with the exception of sand content by sub-county, which was significantly different between Butansi and Namasagali sub-counties (P=0.0347) (though not between Butansi and Bugulumbya). Although we are unable to conclude differences in yields between farms based on their soil physical and chemical properties, due to limited soils data for the on-farm trials, we can note some interesting observations. The two highest yielding farms (Farm No. 6 and Farm No. 9) were both located in Butansi parish in Butansi sub-county. Further, a trend towards a positive relationship between sand content and yield was discussed in Chapter 3, though no significant relationship could be established. Sampling artifacts, however, including sampling only to the 15 cm-depth, provided no information on soil properties below 15 cm, which may change dramatically with depth. Such considerations are especially important, given that grain amaranth is a deep-rooted crop.

If we include results from Farm No. 5 (in Butansi parish within Butansi sub-county), we observed that the highest mean yield among all farms was obtained on this farm (1536.9 kg ha^{-1}), despite his lower application rate of 16.9 ton ha^{-1} of cattle manure. It should be noted that, however, that Farm No. 11, for whom the lowest mean yield was recorded (239.1 kg ha^{-1}) also resides in Butansi sub-county, albeit in Naluwoli parish, while Farm No. 7, another Naluwoli resident, had similarly average yields.

As discussed above, plant health and disease parameters do not appear to provide an explanation for yield differences between farms. Even where these parameters were significantly different between farms, regression analysis indicated no significant impact on yield. The relationship between yield and relative thinning and weeding dates is less clear, but the highest yielding farm, Farm No. 6, had consistently earlier relative weeding and thinning dates. However, this trend was not linear among the other farms.

Variability between soil amendment treatments. There was a significant treatment effect on yields between control plots and those amended with cattle manure (P=0.0083), with log-transformed yields significantly higher for the cattle manure treatment over the control

(Table 10). Amaranth grain yields for the cattle manure treatment averaged 666.7 kg ha^{-1} across all farms, while control plots yielded 420.4 kg ha^{-1}. However, there was considerable variability within each treatment, as standard deviations were 440.5 kg ha^{-1} for cattle manure and 282.8 kg ha^{-1} for the control.

Although manure from each individual farmer was not analyzed prior to application as an amendment treatment, as discussed in Chapter 2 and detailed by Lekasi et al. (2003), manure quality in East Africa tends to be variable in quality depending on numerous exogenous factors. Such factors include the presence or absence of roofing and bedding, animal diet, and animal type. Given that individual farms applied cattle manure derived from their own homestead, variation in manure quality could, in part, account for both differences between farms and soil amendment treatments.

However, the extent to which such variability is realized in the field depends on numerous factors, including nutrient mineralization, and subsequently, plant nutrient availability. Nutrient availability is controlled to a great degree by factors such as soil chemical and physical properties, and weather conditions, particularly precipitation.

Similarly, nutrient mineralization may be facilitated or impeded depending on the suite of soil microorganisms present in the soils under study (Brady and Weil, 1999). Low manure quality and, specifically, a high C:N ratio may precipitate a nitrate depression period following the application of manure due to nutrient immobilization by soil microbes (Brady and Weil, 1999). However, the fact that the cattle manure treatment raised yields significantly indicates that if such nutrient immobilization occurred, it did not last for the duration of the experiment and that N from the manure treatment eventually became plant-available.

Variability between amaranth varieties. There was no significant effect on yields from varieties (P=0.1920). Yield for the "cream" variety averaged 619.1 kg ha^{-1} across all farms, while yield of the "golden" variety averaged 468.0 kg ha^{-1}. Farms exhibited high variability between amaranth varieties: the standard deviation for the "cream" yield was 487.3 kg ha^{-1} and 260.5 kg ha^{-1} for the "golden" yield. Effects were also not significant for interactions of both treatment and variety (P=0.7051) and farm and variety (P=0.1681).

Comparison of on-station and on-farm trials. Mean yields for both varieties were substantially higher in the on-station trial in Kabanyolo than in the farmer-managed trials in the Kamuli District. Average yields for Experiment 2 at the Kabanyolo station, which was conducted in part during the dry season, were approximately double the mean yields for the Kamuli experiment, across all farms, treatments, and varieties. However, the findings for differences between varieties in the on-farm trial followed a similar trend to those discussed in Chapter 3, where the "cream" variety out-yielded the "golden" variety by a significant degree during the rainy season. Although yield differences were not significantly different in the on-station trials, the "cream" variety yield was 44% greater than the "golden" variety. Analysis of the on-station experiments indicated that, while "cream" often maintains higher yields than "golden," the latter may have greater drought tolerance, given that yields between the two varieties were not significantly different for the dry-season Experiment 2 in the on-station trial. The absence of significant varietal differences in yield, coupled with lower yields across the Kamuli trials, may lend support to the idea that precipitation differences between farms was a major determining factor of variation in amaranth grain yields. As will be detailed in the conclusions and recommendations section of Chapter 5, differences in yield between the two sets do not appear related to soil physical and chemical properties.

Protein content

There was no significant difference in amaranth grain protein content between treatments (P=0.6724) or varieties (P=0. 2064) in the on-farm trials (Table 10). Protein content averaged 14%, with or without manure amendments. The “golden” variety averaged 14.2% and “cream” averaged 13.9% protein. There was no significant interaction between treatment and variety (P=0.4304) or between farm and variety (P=0.2384). Following the yield differences observed between farms, protein content also differed between farms (P=0.0009). The highest protein content was recorded on Farm No. 8 at 15.1%, while Farm No. 4 had the minimum protein content at 12.1%. In addition to the previous explanations for variations in yield between farms (e.g., possible precipitation differences), other confounding variables, particularly different cultural practices for weeding, thinning, and planting density, may have affected amaranth protein content. There was a trend towards lower protein content with higher yields in this study (P=0.0691 for protein against actual yield, and P=0.1206 for protein against log yield). Such an inverse relationship may indicate a physiological explanation for differences in protein content, as it appears the amaranth plant may differentially allocate resources to yield or protein content depending on environmental factors, or alternatively, there exists the possibility of sampling error in yield reports.

Amaranth varieties did not differ in protein content, with the “golden” variety averaging 14.2% protein and 13.9% protein for the “cream” variety. Amaranth protein content results from the Kamuli on-farm trials corroborates the hypothesis that amaranth grain protein content varies between farms and perhaps that amaranth protein content in the Kamuli District is below national averages. Nakimbugwe (pers. comm.) reported mean amaranth protein content of 12.5% and 11.7%, for “golden” and “cream,” respectively. Comparison of these data, along with results from the on-station experiments, demonstrates a trend towards higher protein content in the “golden” variety, though differences were not significant in the on-farm Kamuli trials.

As to the causes of the low protein content initially reported by Dr. Nakimbugwe, in light of protein differences we observed between farms in this study, the lower protein content may signify that the amaranth grain in Dr. Nakimbugwe’s analysis was obtained from a random selection of farms, some with lower protein content amaranth grain. The higher protein content of grains from the Kamuli on-farm trials may also indicate selection of on-farm cooperators with greater expertise in growing higher quality amaranth. Alternatively, differences in post-harvest grain handling methods by on-farm cooperators may have resulted in seed damage, sprouting or admixture with foreign material, all of which could reduce protein content of the grains (Lehmann, 1996). Given that protein content for the Kamuli experiments was analyzed at AIB International, Inc. (Manhattan, KS), while Dr. Nakimbugwe’s analysis was performed at Makerere University in Uganda, differences in laboratory analytical methods may represent an additional possible cause of variation in protein content between the two analyses. Chapter 5 summarizes all on-station and on-farm trials together and presents recommendations for future organic amaranth production in Uganda.

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Table 1. Physical and chemical properties for upper 15 cm of soil from on-farm experimental trial sites in Kamuli District, Uganda.

Farm No.	Sub-county	Parish	pH	SOM (%)	N (%)	P	K	Na	Ca	Mg	Ex. bases[1]	Sand	Clay	Silt
						mg kg^{-1}	-------------------Cmoles$_c$ kg^{-1}---------------					------------%----------		
1	Bugulumbya	Nawanende	4.9	2.41	0.11	7.06	2.72	0.09	4.6	1.79	9.2	66	22	12
2	Bugulumbya	Nawanende	5.4	3.46	0.19	38.80	1.62	0.08	3.5	1.00	6.2	52	30	18
3	Bugulumbya	Kasambira	6.4	2.12	0.09	5.57	1.86	0.09	3.4	1.84	7.2	64	20	16
4	Namasagali	Namasagali	5.6	1.89	0.10	6.58	0.36	0.07	4.0	1.70	6.1	60	18	22
5	Butansi	Butansi	5.8	3.20	0.20	7.39	0.40	0.08	3.6	1.38	5.5	60	24	16
6	Butansi	Butansi	5.5	2.37	0.16	6.47	0.40	0.08	3.6	1.38	5.5	72	18	10
7	Butansi	Naluwoli	5.5	2.17	0.11	8.47	0.57	0.07	5.5	1.35	7.5	60	28	12
8	Namasagali	Kasozi	6.0	1.65	0.12	7.23	0.80	0.07	4.5	1.35	6.7	68	24	8
9	Butansi	Butansi	5.2	3.68	0.20	7.16	0.63	0.11	5.2	1.80	7.7	64	24	12
10	Bugulumbya	Kasambira	5.7	2.37	0.12	36.27	0.77	0.04	3.9	1.18	5.9	72	18	10
11	Butansi	Naluwoli	6.4	2.68	0.18	8.59	0.98	0.06	4.8	1.31	7.2	60	22	18
Mean			5.7	2.55	0.14	12.69	1.01	0.08	4.2	1.46	6.8	63	23	14

[1] Exchangeable bases used as cation exchange capacity fails to account for H+ occupying exchange sites.

Table 2. Mean plant height by farm number, variety, and treatment for the first three farm visits from on-farm experimental trial sites in Kamuli District, Uganda.

		Height (cm)	
Farm No.	Farm visit 1	Farm visit 2	Farm visit 3
1	4.9c[1]	32.8abc	63.9b
2	5.9c	22.8c	48.5b
3	9.7c	49.5ab	94.9ab
4	21.1ab	52.2a	79.8ab
6	23.7a	47.4abc	113.8a
7	12.3bc	26.5bc	63.8b
8	7.3c	22.9c	53.5b
9	9.5c	35.5abc	70.5ab
10	8.4c	44.5abc	88.8ab
11	13.0bc	26.0bc	70.2ab
Variety			
Cream	11.6a	34.0a	69.1a
Golden	11.6a	38.0a	71.7a
Treatment			
Cattle manure	13.3a	41.8a	86.9a
Control	9.9a	30.2b	62.7b

[1]In each column, means followed by the same letter are not significantly different at P>0.05 (LSD test).

Table 3. Mean plant height by farm number, variety, and treatment for the last three farm visits from on-farm experimental trial sites in Kamuli District, Uganda.

	Height (cm)			
Farm No.	Farm visit 4	Farm visit 5	Farm visit 6	Harvest
1	101.5bc[1]	131.2bcd	150.2ab	152.8bcdd
2	104.1bc	147.9abcd	168.5ab	172.0abc
3	147.7ab	175.3abc	201.0a	201.0ab
4[2]	107.2bc	133.6bcd		133.3cd
6	183.4a	202.3a	204.5a	204.5ab
7	100.0bc	122.9bcd	134.6ab	134.6cd
8	79.5c	103.8d	115.5b	115.5d
9	94.8bc	109.4cd	112.5b	150.9bcd
10	137.0abc	179.3ab	206.7a	206.6a
11	123.1abc	150.4abcd	161.8ab	161.6abcd
Variety				
Cream	122.4a	154.8a	169.1a	179.0a
Golden	113.2a	136.4b	143.5b	147.5b
Treatment				
Cattle manure	133.7a	163.7a	180.4a	175.5a
Control	101.9b	127.5b	143.0b	151.0b

[1]In each column, means followed by the same letter are not significantly different at P>0.05 (LSD test).

[2]Farm No. 4 was visited on only five occasions.

Table 4. Mean percentage of healthy plants by farm number, variety, and treatment for the first three farm visits from on-farm experimental trial sites in Kamuli District, Uganda.

	Healthy plants (%)		
Farm No.	Farm visit 1	Farm visit 2	Farm visit 3
1	66.3ab[1]	80.0b	87.5ab
2	85.0ab	75.0b	80.0b
3	82.5ab	85.0ab	85.0ab
4	100.0a	100.0a	92.5ab
6	46.3b	100.0a	97.5a
7	100.0a	92.5ab	92.5ab
8	100.0a	100.0a	100.0a
9	75.0ab	93.8ab	87.5ab
10	100.0a	100.0a	100.0a
11	90.0a	90.0ab	85.0ab
Variety			
Cream	84.0a	91.5a	90.5a
Golden	85.0a	91.8a	91.0a
Treatment			
Cattle manure	94.3a	96.5a	97.5a
Control	74.8b	86.8b	84.0b

[1]In each column, means followed by the same letter are not significantly different at P>0.05 (LSD test).

Table 5. Mean percentage of healthy plants by farm number, variety, and treatment for the last two farm visits from on-farm experimental trial sites in Kamuli District, Uganda.

	Healthy plants (%)	
Farm No.	Farm visit 4	Farm visit 5
1	87.5abc[1]	75.0a
2	80.0bc	75.0a
3	82.5abc	75.0a
4	85.0abc	85.0a
6	87.5abc	80.0a
7	93.8ab	87.5a
8	93.8ab	90.0a
9	77.5c	68.8a
10	97.5a	92.5a
11	80.0bc	80.0a
Variety		
Cream	87.5a	84.3a
Golden	85.5a	77.5a
Treatment		
Cattle manure	94.0a	89.0a
Control	79.0b	72.8b

[1]In each column, means followed by the same letter are not significantly different at P>0.05 (LSD test).

Table 6. Mean percentage of diseased plants by farm number, variety, and treatment for the first three farm visits from on-farm experimental trial sites in Kamuli District, Uganda.

	Diseased plants (%)		
Farm No.	Farm visit 1	Farm visit 2	Farm visit 3
1	0.0a[1]	0.0b	0.0b
2	0.0a	0.0b	0.0b
3	0.0a	15.0a	15.0a
4	0.0a	0.0b	0.0b
6	0.0a	0.0b	0.0b
7	0.0a	7.5ab	7.5ab
8	0.0a	0.0b	0.0b
9	0.0a	0.0b	0.0b
10	0.0a	0.0b	0.0b
11	0.0a	0.0b	0.0b
Variety			
Cream	0.0a	2.5a	2.5a
Golden	0.0a	2.0a	2.0a
Treatment			
Cattle manure	0.0a	0.5a	0.5a
Control	0.0a	4.0a	4.0a

[1]In each column, means followed by the same letter are not significantly different at P>0.05 (LSD test).

Table 7. Mean percentage of diseased plants by farm number, variety, and treatment for the last two farm visits from on-farm experimental trial sites in Kamuli District, Uganda.

	Diseased plants (%)	
Farm No.	Farm visit 4	Farm visit 5
1	2.5b[1]	5.0b
2	0.0b	0.0b
3	15.0a	15.0a
4	0.0b	0.0b
6	0.0b	0.0b
7	7.5ab	7.5ab
8	0.0b	0.0b
9	0.0b	0.0b
10	2.5b	2.5b
11	0.0b	0.0b
Variety		
Cream	3.5a	3.5a
Golden	2.0a	2.0a
Treatment		
Cattle manure	0.5a	0.5a
Control	5.0a	5.0a

[1]In each column, means followed by the same letter are not significantly different at P>0.05 (LSD test).

Table 8. Mean percentage of plants with damaged leaves by farm number, variety, and treatment for the first three farm visits from on-farm experimental trial sites in Kamuli District, Uganda.

	Plants with damaged leaves (%)		
Farm No.	Farm visit 1	Farm visit 2	Farm visit 3
1	33.8ab[1]	75.0a	84.8a
2	18.8abc	45.0ab	62.5ab
3	27.5abc	35.0b	42.5bcd
4	13.8bc	25.0b	35.0cd
6	41.3a	52.5ab	60.0abc
7	11.3bc	18.8b	25.0d
8	7.5bc	28.8b	45.0bcd
9	23.8abc	35.0b	47.5bcd
10	5.0c	21.3b	32.5d
11	16.3abc	25.0b	40.0bcd
Variety			
Cream	18.0b	34.0a	43.0b
Golden	21.8a	38.3a	52.0a
Treatment			
Cattle manure	19.8a	36.5a	45.0a
Control	20.0a	35.8a	50.0a

[1]In each column, means followed by the same letter are not significantly different at P>0.05 (LSD test).

Table 9. Mean percentage of plants with damaged leaves by farm number, variety, and treatment for the last two farm visits from on-farm experimental trial sites in Kamuli District, Uganda.

	Plants with damaged leaves (%)	
Farm No.	Farm visit 4	Farm visit 5
1	87.3a[1]	87.3a
2	75.0ab	79.8ab
3	47.5bc	50.0b
4	52.5bc	70.0ab
6	70.0ab	77.5ab
7	35.0c	57.5ab
8	60.0abc	74.8ab
9	70.0ab	75.0ab
10	75.0ab	75.0ab
11	50.0bc	52.5b
Variety		
Cream	56.0b	62.0b
Golden	68.5a	77.9a
Treatment		
Cattle manure	57.5a	65.0a
Control	67.0a	74.9a

[1]In each column, means followed by the same letter are not significantly different at P>0.05 (LSD test).

Table 10. Mean amaranth grain yield and protein content by farm number, variety and treatment from on-farm experimental trial sites in Kamuli District, Uganda.

Farm No.	Grain yield (kg ha^{-1})	Log yield[1]	Protein content
1	327.9	5.63cd	13.9bcd
2	409.9	6.00bcd	14.8ab
3	341.5	5.79bcd	14.8ab
4	519.2	6.25bc	12.1e
6[2]	1229.5	7.02a	13.0de
7	505.5	6.22bc	13.6cd
8	375.7	5.75bcd	15.1a
9	770.3	6.46ab	14.2abc
10	707.7	6.40ab	15.0a
11	239.1	5.40d	14.3abc
Variety			
Cream	619.1	6.17a	13.9a
Golden	468.0	6.01a	14.2a
Treatment			
Cattle manure	666.7	6.34a	14.1a
Control	420.4	5.84b	14.0a

[1]Amaranth grain yields were log-transformed in the statistical model to control for variance.

[2]Includes possible data outlier for “cream” variety with cattle manure for Farm No. 6.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

This thesis project involved an in-depth study of amaranth production in the Kamuli District of Uganda in 2009–2010. In June 2009, a series of 34 personal interviews with smallholder farmers in the Kamuli District revealed that grain amaranth is being grown across a wide demographic range of farmers on a number of geographic scales and soils. Most of the respondents reported growing amaranth on fairly small plots of land that had previously supported a wide range of crops. Amaranth was most frequently grown in pure stands, with "golden" as the most common variety. Pest pressure was generally moderate to low in severity. Most respondents did not utilize organic soil amendments to improve crop yields, but those who did apply amendments primarily used cow manure. Soil amendments were variable as to residue age and manure management practices, but most respondents felt the manure they applied was of fairly high quality.

The interviews and survey were complemented by on-station and on-farm experiments testing the effects of organic soil amendments on grain amaranth yields and protein content. Several parameters of amaranth plant growth and productivity were measured, including leaf number and plant height. The on-station trials were the only experiment where data on leaf number was obtained. In this case, the addition of soil amendments provided no statistical increase in productivity in terms of leaf number in Experiments 2 and 3, and only a numerical increase in leaf number 1 of 14 sampling times in both experiments. Average leaf number was 88.6 leaves per plant for Experiment 2 and 99.6 leaves per plant for Experiment 3.

The addition of soil amendments provided a statistical increase in productivity in terms of plant height across all on-farm trial sites on all sampling periods (2 to 7) except the first date. Looking at amaranth plant height on each of the 10 farms on the first sampling date, there were statistically significant differences in plant height between farms, with the average height at 12.5 cm with a standard deviation (SD) of 8.1 cm. From the second to the seventh sampling date (harvest), there were no significant differences between farms, as plant height increased from an average of 17.8 cm (SD: 5.8 cm) to 159.0 cm (SD: 49.7 cm). Numerical increases in plant height are also presented here because farmers tend to register any increase in productivity, statistical differences notwithstanding. A numerical increase in amaranth plant height with the addition of soil amendments occurred a total of 107 of 138 sampling times across all on-farm trial sites.

In the on-station experiments, the addition of soil amendments did not provide a statistical increase in productivity in terms of plant height in either Experiment 2 or Experiment 3, but there was a numerical increase in plant height with soil amendments a total of 16 of 28 sampling times. The average amaranth plant height in Experiment 2 was 102.8 cm, while plant height in Experiment 3 was 57.4, 92.6, and 109.7 cm at 35, 50 and 57 DAP, respectively. Over both on-farm and on-station experiments, there was a numerical increase in plant height a total of 107 of 142 sampling times.

Values for plant height and plant leaf number obtained in these experiments were similar or greater than those cited in the literature, as discussed in Chapter 3 and Chapter 4 (Nyankanga, pers. comm.; Olaniyi, 2007). Thus, it appears that the addition of soil amendments may increase vegetative growth of amaranth, which may be particularly important for vegetable amaranth production.

Regarding grain yield effects, the addition of soil amendments provided a statistical yield increase in the on-farm experiments in the Kamuli District, where treatment averages were 666.7 kg ha^{-1}, compared to 420.4 kg ha^{-1} in control plots, representing a yield increase of 58.6% with the addition of cattle manure. Numerical yield increases with soil amendments occurred a total of 18 of 20 times. However, there was considerable variability within each treatment, as standard deviations in terms of log yield were 0.55 and 0.63 for cattle manure and control treatments, respectively. Yield differences between varieties were not significantly significant, averaging 619.1 kg ha^{-1} for “cream” and 468.0 kg ha^{-1} for “golden” (SD: 487.3 kg ha^{-1} and 260.5 kg ha^{-1}, respectively).

Statistically significant yield increases with the addition of soil amendments were not observed in the on-station Experiments 2 or 3. There was, however, a numerical increase in yield with soil amendments a total of 9 of 12 times in the on-station experiments. Average on-station amaranth grain yields were 1110.4 kg ha^{-1} (SD: 65.8 kg ha^{-1}) in Experiment 2, and 1886.1 kg ha^{-1} (SD: 921.1 kg ha^{-1}) in Experiment 3. Yields by variety were significantly different in both Experiment 2 and 3. In Experiment 2, yields of “cream” and “golden” varieties averaged 1013.1 kg ha^{-1} and 1207.7 kg ha^{-1}, respectively, which were significantly higher than ‘Plainsman’ at 194.1 kg ha^{-1} (SD: 62.6 kg ha^{-1}). In Experiment 3, yields for “cream”, at 2750.2 kg ha^{-1} (SD: 846.8 kg ha^{-1}), were significantly greater than those of “golden” and ‘Plainsman’ which obtained yields of 1742.3 kg ha^{-1} and 1165.6 kg ha^{-1}, respectively (SD: 718.6 kg ha^{-1} and 296.7 kg ha^{-1}).

Although statistical analysis of protein content from both on-station experiments was not possible, there was a numerical increase a total of 6 of 11 times in Experiments 2 and 3. Mean protein content across all treatments and varieties in Experiment 2 was 14.5% (SD: 0.2%), while Experiment 3 grain had a mean protein content of 15.1% (SD: 0.2%). Similarly, in the on-farm experiments, the addition of soil amendments did not provide a statistical increase in protein content, but there were numerical increases a total of 8 of 18 times across all farms. The average protein content was significantly different between farms, ranging from 15.1% for Farm No. 8 to 12.1% for Farm No. 4. Thus, the addition of soil amendments provided a numerical increase in protein content a total of 14 of 29 times across all experiments. Protein content was not significantly different between varieties, with “cream” averaging 14.2% and “golden” 13.9%.

Amaranth grain yields reported in the literature vary depending on such factors as soil chemical and physical properties, climate, planting density, planting time, variety, and level of fertilization. Yield results for Kabanyolo on-station experiments were similar to those reported in the literature, while yields from the on-farm trials were on the low end of the spectrum (Brenner et al., 2000; Bressani et al., 1987; Elbehri et al., 1993; Gupta et al., 1992; Joshi and Rana, 1991; Myers, 1998; Nyankanga, pers. comm.; Olaniyi, 2007). However, both sets of experiments exhibited considerable variability, with the on-station experiments demonstrating a large degree of plot level variability. Similarly, there was a significant degree of variation between farms in the on-farm trials, with some farmers obtaining significantly higher yields than others.

Concerning variability in yields between farms in relation to soil properties, analysis of data collected for soils in the on-farm trials indicated positive, but not significant relationships, between yields and some soil physical and chemical properties. On-station trials presented the possibility of a positive relationship between sand content in soil and amaranth yields, as yields were significantly greater in Column 3 of that experiment, where sand content tended to be highest (Johnson and Henderson, 2002; Putnam, 1990).

The on-farm experiments also indicated that there was a significantly positive relationship between later planting dates and yield, while there was a negative, but not significant relationship, between planting density and yield. However, it should be noted that there was a significantly negative relationship between planting date and planting density. Cultural practices, such as earlier and more frequent weeding, also tended to increase yields, but not significantly. Parameters related to plant health and disease were inconsistent and indicated that these variables did not significantly impact yields, despite instances of significant differences between farms for these parameters.

Differences in amendment quality portend another possible source of variation in yields between farms. For example, data from Farm No. 5, though not included in the statistical analysis, showed higher yields than any other farms, despite this farmer’s statement of a lower application of cattle manure compared to the other farmers. Further, although manure from each individual farmer was not analyzed prior to application as an amendment treatment, as discussed in Chapter 2, manure quality in East Africa tends to be variable in quality depending on numerous exogenous factors (Lekasi et al., 2003; Murwira et al., 1994; Saleem, 1998). Such factors include the presence or absence of roofing and bedding, animal diet, and animal type. However, values for manure nutrients are generally lower than those found in the developed world. Given that individual farmers applied cattle manure derived from their own homestead, variation in manure quality could, in part, account for yield differences between farms and between varieties.

Yields from the on-station experiments were substantially higher than those for on-farm trials, despite ostensibly similar site characteristics and purportedly higher amendment application rates in the on-farm experiment. However, this is not entirely unexpected given that yields from on-station trials tend to be consistently higher than those of on-farm trials (van Bruggen, 1995). In this instance, there are several reasons why this might have been the case. Particularly, the absence of data on precipitation, which can be quite variable in the area of the study (Kizza et al., 2009; Phillips and McIntyre, 2000), as well as the possibility of lower soil fertility at the on-farm sites (limited by incomplete soil analysis), suggests the possibility that either of these two factors may be responsible for the increased yields in Kabanyolo over the Kamuli on-farm experiments.

Another possible explanation for differences in yields between on-farm and on-station experiments relates to site history. While soil physical and chemical properties were relatively similar between Kabanyolo and Kamuli, the Kabanyolo on-station site had been under perennial vegetation, and thus not tilled, for at least a decade. By contrast, most plots in the Kamuli study area had historically been planted in annual crops and were thus subjected to tillage at regular intervals, soil nutrient depletion by previous crops, soil compaction, and possible creation of plow pans. The extended interval between tillage for the on-station experiment, as well as the fact that the site was subjected to more intensive tillage in the form of mechanized disking and harrowing prior to amaranth planting, suggests the possibility of increased mineralization of soil organic matter in the on-station experiments with associated increases in yields (Cambardella, 2010; Pekrun et al., 2003; Seiter and Horwath, 2004). Finally, daily attention to the amaranth plants and plots at the research station by a Makerere University student, in contrast to plot maintenance by farmers with multiple responsibilities, may have influenced yield response. In sum, increased yield for the on-station trials over on-farm experiments may be due to a suite of factors rather than any individual cause.

Yields for the “cream” variety tended to be higher than those for the “golden” variety in both the on-station and on-farm experiments; however, this effect was only significant in Experiment 3 of the on-station trials. Comparison of varieties across all experiments indicated that while “cream” usually produced higher yields, the “golden” variety may demonstrate greater drought tolerance.

Similarly, while the “golden” variety appeared to have higher protein content compared to “cream”, this effect was not significant in the on-farm experiments. Both varieties had protein content comparable to those found in literature, if on the lower end of the spectrum (Bressani, 1989; Bressani, 1994; Bressani et al., 1987; Senft, 1980). The foregoing information begs the question as to the causes of the low protein content initially reported by Dr. Nakimbugwe. Given that there were significant differences in protein content between farms for the on-farm experiments, the lower protein content reported for both varieties may signify that the amaranth grain used for Dr. Nakimbugwe’s analysis was obtained largely from farmers with low-protein content amaranth grain. The higher protein content of grains from the Kamuli on-farm trials may also indicate a sampling bias on the part of the experiment towards farms with relatively higher protein content. Alternatively, differences in post-harvest grain handling methods by on-farm cooperators may have resulted in seed damage, sprouting or admixture with foreign material, all of which could reduce protein content of the grains (Lehmann, 1996). Given that protein content for the Kamuli experiments was analyzed at AIB International, Inc. (Manhattan, KS), while Dr. Nakimbugwe’s analysis was performed at Makerere University in Uganda, differences in laboratory analytical methods may represent a possible cause of variation in protein content between the two analyses.

In conclusion, these experiments and survey results demonstrated a widespread use, and acceptable productivity, of amaranth as a high-quality protein food source for farmers in the Kamuli District in Uganda. Additional experiments are needed to further evaluate the role of organic soil amendments on amaranth yield and protein content under more controlled conditions. Linkages with organic associations, such as NOGAMU (National Organic Agriculture Movement of Uganda, Kampala, Uganda, 2010), can help facilitate marketing strategies for amaranth farmers whose production exceeds family needs and desire to enter commercial markets.

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APPENDIX I: AMARANTH SURVEY

Survey of Amaranth in Kamuli

Name: ________________________ (optional)

Location: ____________________________

Soil Type:____________________________

Background information

Interviewer: …………………………………………………

Date: ……………………………

Name of farmer:………………………………………...…………………

Village:…………………………..

Parish:…………………………………………………….

County:……………………………

Sub-county:……………………………………………...

District:……………………………

Sex of farmer:…………………….

Age of farmer:…………………………………………

Soil type:…………………….

Field History

1. What crops have you grown in the past 3 years on the ground where you are now growing amaranth?

2. The weather has been: regular irregular mixture

3. Please estimate the rainfall for this year: ___________ ___________ ___________

4. During which months did the rains come this year? ______ ______ ______

5. Area planted in amaranth last season?

Cultivation

6. What varieties of amaranth have you planted?

7. How long after rains began was it planted?

8. Do you grow amaranth as a pure stand or as an intercrop? 1. Pure 2. Intercrop 3. Both

9. If intercrop, what are the intercrops? 1 _______________ 2_______________

3________________4_______________

10. Did you use seeds or transplants?

11. How long did the crop take to mature?

12. Was tillage used? If so, what type?

13. Were plants thinned and/or leaves eaten as vegetables? Yes No

14. Were animal residues (manure or compost) used on land for this crop? Yes No

15. Were any pesticides used?

16. If yes, how frequently, how much, and what type?

Amendments

17. What type of residues were used?

18. What type(s) of animals produced the manure?

19. Were any other materials added? If so, what?

20. How old was the manure? __________ __________ __________

21. Was the pile turned regularly? How often?

22. How would you assess the quality on a scale? (Low) 1 2 3 4 5 (High)

23. When were residues applied?

24. How was it incorporated?

25. How would you rate your insect problems? Low Medium High

26. How would you rate your weed problems? Low Medium High

27. Do you have birds eating your seed? Yes No

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