Conservation agriculture in Senegal: comparing the effects of intercropping and mulching on millet yields

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Abstract

Situated on the western edge of Africa's harsh Sahel region, Senegal faces a number of agricultural production constraints. Limited rainfall, poor soil fertility, and insufficient agronomic inputs all contribute to low yielding millet production systems. This study was initiated to assess the potential for intercropping either cowpea (*Vigna unguiculata* (L.) Walp.) or mungbean (*Vigna radiata* (L.) Wilczek) into traditional pearl millet (*Pennisetum glaucum* (L.) R. Br.) cropping systems. During the 2013 and 2014 growing seasons two varieties of cowpea (upright and viney), and one variety of mungbean (upright) were grown in monoculture and subsequently intercropped with millet to evaluate the potential for increasing millet and overall yields. Millet was also planted with a mulch (2 t/ha of neem leaves) to test the effectiveness of increased ground cover on millet yields. In addition to yield data, soil moisture and plant NDVI data were also collected. Millet grain yields increased when intercropped with either cowpea or mungbean compared to millet that was grown alone, with grain yield increases of up to 55%. Additionally, the combined grain yields (millet + bean) were up to 67% higher than the traditional monoculture millet. The addition of mulch was the most effective treatment and increased millet grain yields up to 70%. Soil moisture increased up to 14% in mulched treatments over millet monoculture treatments. All yield increases were achieved without the addition of fertilizers or nutrient amendments. In an attempt to mimic local practices our experiment was rainfed and no soil amendments were introduced.

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List of Abbreviations

CA	–	Conservation Agriculture
CEC	–	Cation Exchange Capacity
ENSA	–	École Nationale Supérieur d'Agriculture
ERA	–	Education & Research in Agriculture
ISFAR	–	Institut Supérieur de Formation Agricole et Rurale
ISRA	–	Institut Sénégalais de Recherches Agricoles
LER	–	Land Equivalency Ratio
NDVI	–	Normalized Difference Vegetation Index
RCBD	–	Randomized Complete Block Design
USAID	–	U.S. Agency for International Development
VWC	–	Volumetric Water Content
WAMP	–	Weeks After Millet Planting
WASAT	–	West African Semi-Arid Tropics

Chapter I: Introduction

While Senegal is one of the most stable economies in West Africa, it continues to struggle with the needs of a growing population. Although Senegal produces a wide array of agricultural commodities for export, such as peanuts, sugarcane, and rice, it remains a net food importer (UNDATA, 2013). The majority of agricultural production is at the subsistence level and remains susceptible to the harsh conditions of the Sahel region within which it lies. This region of the world, also known as the West African Semi-Arid Tropics (WASAT), is characterized by low and erratic rainfall, high temperatures, and inherently poor soils. These conditions are being exacerbated by population growth and the need to produce more food on the same amount of land.

Traditional methods of farming, which once included long fallow periods of 7 years or more (Bationo *et al.*, 1993), have been greatly altered, with the practice of fallowing now abandoned on many farms. This, combined with little to no fertilizer additions and the habitual removal of all crop residues (traditionally used for livestock feed, fuel, and building materials), has left soils bare and generally deficient in nutrients and organic matter. Soils in this region therefore tend to have poor soil structure, higher rates of erosion, low cation exchange capacities (CEC), low water-holding capacities, and general nutrient deficiencies.

Under these constraints and current farmer practices, the average smallholder farmer in Senegal will struggle to sustain sufficient yields and maintain soil fertility. Until the average smallholder farmer gains access to adequate fertilizers, reasonable solutions must be presented to local farmers that can address these limitations with the resources at hand. It is therefore the objective of this study to evaluate agronomic practices that have the potential to increase yields without the use of expensive inputs that farmers may not have the means to acquire. The practices evaluated in these studies followed the guiding principles of Conservation Agriculture (CA) and were focused on increasing yields of two of Senegal's major subsistence crops, pearl millet (*Pennisetum glaucum* (L.) R. Br.) and cowpea (*Vigna unguiculata* (L.) Walp.). Both crops are widely produced within most of the country and play a large role in the consumption habits of most smallholder farmers.

This research focused on enhancing local food security by improving the productivity and sustainability of millet-cowpea systems of central Senegal. We evaluated the effects of growing legumes in association (intercropping) with the primary cereal crop of millet. Two cowpea varieties (upright and viney) and one mungbean variety (*Vigna radiata* (L.) Wilczek) were evaluated based on their ability to boost overall grain yields when intercropped with millet. The specific objectives were:

Specific objectives of this study are to evaluate:

1. The effects of intercropping vs. monocropping on grain yields.
2. The potential for intercropping cowpea or mungbean between millet rows without driving down millet yields.
3. The impact of increased ground cover from intercropping and mulching practices on soil moisture retention.
4. Mungbean as a potential alternative to cowpea in Senegal's millet-cowpea systems.

Chapter II: Literature Review

The West-African Sahel

The Sahel region of Africa refers to the semiarid transition zone that lies between the Sahara Desert in the north and the Sudanian Savannas to the south (Grove, 1978). The Sahel is roughly situated between 10 and 20^{o} N and extends from Senegal in the west, to Ethiopia in the east (Sinclair and Fryxell, 1985). The West-African Sahel refers more specifically to the areas of the West African countries that fall within this zone; these include portions of Senegal, Mauritania, Mali, Niger, Burkina Faso, and Chad (Matlon, 1987). Climatic conditions in the region are characterized by high temperatures and low moisture. Precipitation falls in a unimodal pattern and is limited to the short, wet summers from June to October, followed by prolonged dry periods for the remainder of the year (Hoogmoed and Stroosnijder, 1984). Average annual rainfall ranges from 250 to 750 mm and falls sporadically over a period of 60 to 120 days (Matlon, 1987) (L'Hôte *et al.*, 2002).

Low rainfall is not the only major constraint on agricultural production in the region. Soil fertility in the Western Sahel is characteristically poor and limiting to agricultural production. Soils in this region have particularly low percentages of clay and organic matter and thus low cation exchange capacities, making them highly susceptible to nutrient depletion (Matlon, 1987).

Millet

The millets are small-seeded cereal grains adapted to the hot and dry climates of the world (Hulse *et al.*, 1980). Millet, which is typically grown in Africa and India, could be considered the cereal grain of the marginal land as it is capable of growing where other grains would normally fail. The crop will produce grain on soils that are too sandy or rocky, too acidic, too dry, and too infertile for other crops such as maize and sorghum to grow (Stoskopf, 1985). Millets are valued for their hardiness and drought tolerance, and are capable of growing in regions receiving as little as 300 mm of seasonal rainfall (Dendy, 1995). A maize crop typically requires a minimum of 500-600 mm and sorghum, also known for its drought tolerance, requires at least 400 mm (Dendy, 1995). Of the eight major cereal grains, millet has the highest water-use efficiency, approximately two and a half times that of rice (Stoskopf, 1985).

According to the Food and Agriculture Organization's 2012 report, millet production ranked as the sixth most important cereal worldwide behind wheat, maize, rice, barley, and sorghum (FAOSTAT, 2012). Worldwide production in 2013 was 30 million tonnes, with India accounting for nearly half of this number; India produced 10.91 million tonnes of millet in 2013 (FAOSTAT, 2013d). Other important millet producing countries include the West African nations of Nigeria, Niger, Mali, and Burkina Faso (Figure 1) (FAOSTAT, 2013d). In the United States and Australia millet is grown primarily as a forage crop (Stoskopf, 1985).

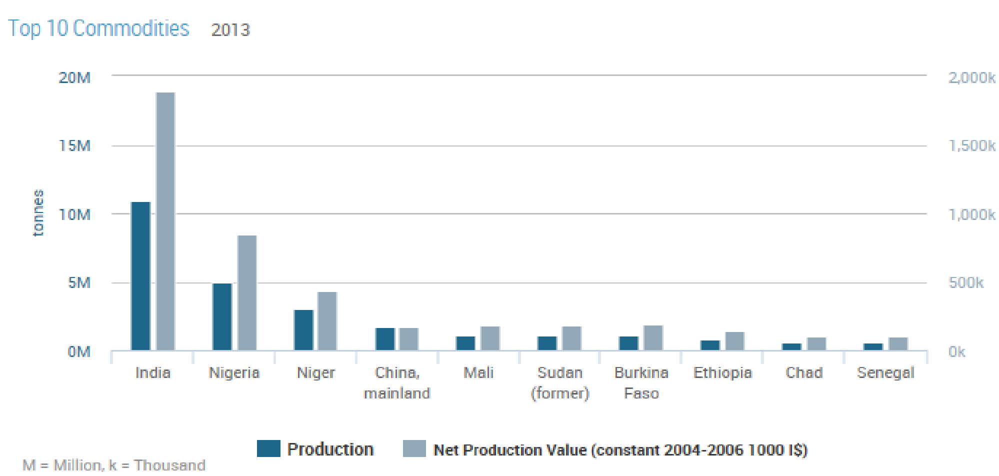


Figure 1. Top 10 millet producing countries in 2013 (FAOSTAT, 2013d)

Worldwide production includes a variety of different cultivated millets with the majority of production belonging to a few individual species. These include but are not limited to, pearl millet (*Pennisetum glaucum* (L.) R. Br.), finger millet (*Eleusine coracana* (L.) Gaertn.), foxtail millet (*Setaria italia* (L.) P. Beauv.), proso millet (*Panicum miliaceum* (L.)) and teff (*Eragrostis tef* (Zuccagni) Trotter) (Germplasm Resources Information Network, 2009).

Pearl Millet (*Pennisetum glaucum* (L.) R. Br.)

Pearl millet (*Pennisetum glaucum* (L.) R. Br.), also commonly referred to as bulrush millet, cattail millet, or bajra in India, is the most widely grown of all the millet species (FAOSTAT, 1996). According to the 1996 United Nations Food and Agriculture Organization annual report, Pearl millet accounted for 55% of the millet grown in developing countries (FAOSTAT, 1996). It is also one of the oldest documented crops with archaeological evidence suggesting its use as early as 4000 B.C. in West Africa (Manning *et al.*, 2011) (Amblard and Pernes, 1989). Scientists have also come to the consensus that pearl millet is indigenous to the very same region, the Sahel region of western Africa (Harlan, 1971) (Hulse *et al.*, 1980).

Pearl millet, a member of the Poaceae family, is an annual C4 grass that typically grows anywhere from 1.5 m to 3 m tall. It is an erect and fast growing bunch-type grass (Stoskopf, 1985). Pearl millet is easily recognizable at maturity with its stiff, cylindrical inflorescences which are typically 15 to 45 cm in length (Devos *et al.*, 2006) and produce 500 to 3000 grains per head, depending on size (Andrews *et al.*, 1993). Seeds range in color from light gray, deep gray, and pearly amber to deep yellow and purple (Athwal, 1966) and are described as *obovoid*, or egg-shaped, and range from 3 to 4 mm long and 2.25 mm wide (Stoskopf, 1985).

Pearl millet is highly tillering and produces 2 to 3 times more heads per plant than sorghum grown in similar densities (Andrews *et al.*, 1993). Leaves, sheaths, and nodes may be smooth or hairy, and range in color from green, purple, red and yellow (Stoskopf, 1985), while leaf blades are flat, cordate, and up to 1 m long and 5 cm wide (Devos *et al.*, 2006). Stems are solid, not hollow, and typically range from 1 to 2 cm in diameter (Rachie and Majmudar, 1980). Plants typically have anywhere from six to twelve internodes with the internode length increasing from the bottom to the top of the stalk. Primary tillers arise from a group of closely spaced internodes just under the ground (Stoskopf, 1985). Pearl millet produces prop roots used to help support the plant, one seminal root, and a secondary root system that has the potential to penetrate as deep as 5 m (Rachie and Majmudar, 1980).

Pearl millet can be divided into categories depending on maturity types, which include early, medium, and late maturing types. Early millet matures within 60-95 days, while late millet matures in 130-150 days (Hulse *et al.*, 1980). Seedling development over the course of the first month is relatively slow as the majority of photosynthate is directed to root development; this characteristic makes the plant susceptible at early stages to weeds, which tend to grow faster and out compete the millet (Stoskopf, 1985).

High biomass production can be observed in traditional pearl millet cultivars and occurs mostly during short periods of favorable conditions. It is thought that this adaptive feature helps maintain the plant through periods of stress such as low fertility, pest damage and weed competition (Andrews *et al.*, 1993). However, this results in relatively low harvest indexes. According to one study in Nigeria, researchers found that using a local variety of pearl millet (cv. Ex Bornu) produced 22 t/ha of above ground dry matter, with only 3.2 tons of this as grain; accounting for a harvest index of only 14.5% (Kassam and Kowal, 1975). An additional study completed in Australia observed average harvest indexes of 30% in pearl millet compared to indexes of 36% and 47% in sorghum and maize respectively (Muchow, 1989).

Millet Production in Senegal

Millet is the most extensively grown grain in Senegal and follows only sugarcane and groundnut in tonnes produced each year (Figure 2) (FAOSTAT, 2013c); an average of 0.5 million tonnes were produced annually between 1990 and 2013 (FAOSTAT, 2013a). Pearl millet in Senegal is often grown in rotation (or intercropped) with groundnut, cowpea, or sorghum (Rachie and Majmudar, 1980). It is well suited to grow on a wide range of soils but typically does best in regions characterized by sandy, well drained soils (Rachie and Majmudar, 1980). Although pearl millet is typically grown on very poor soils, it responds well to nutrient applications and has a remarkable ability to extract nutrients from soils of low fertility (Hart and Burton, 1965).

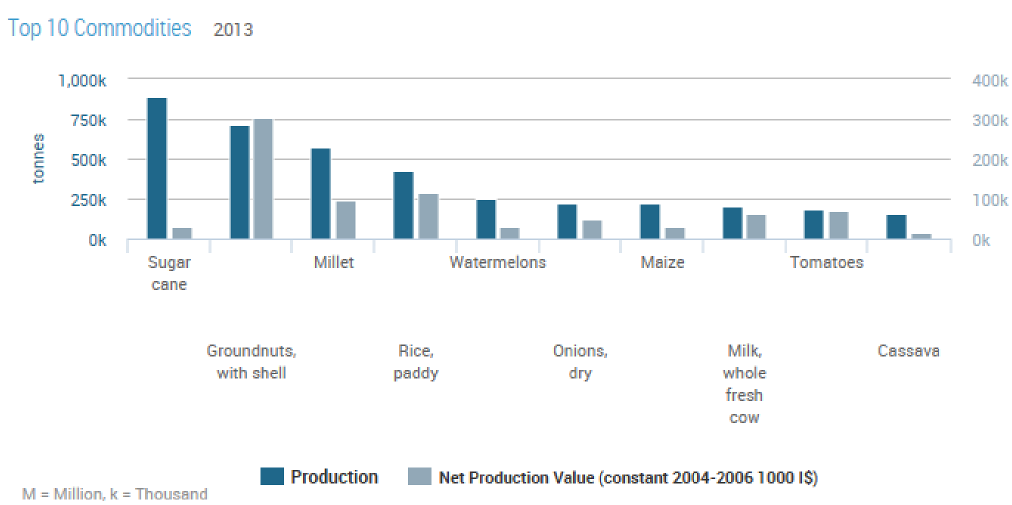


Figure 2. Top 10 Food and Agricultural Commodities Produced in Senegal in 2012 (FAOSTAT, 2013c)

While low rainfall is the primary yield limiting factor in Senegal (250 to 750 mm annually), so too is poor soil fertility. Some researchers have concluded that soil fertility is in fact the primary limitation to improving crop yields in the millet producing regions of West Africa (Fussell *et al.*, 1989). While moisture and soil fertility are both crucial to growth, the timing of the moisture and fertilizer availability during the developmental phase of the plant is what is most crucial to grain yield. In one study conducted in Senegal (Vidal, 1962) it was determined that moisture was the most limiting factor during the 50-day period between sowing and tillering, while a lack of inorganic nitrogen was the limiting factor between tillering and grain production.

Cowpea (*Vigna unguiculata* (L.) Walp.)

Cowpea, which is also commonly referred to in the United States as black-eyed pea, purple-hulled pea, or crowder pea; frijole or caupi in Brazil; and niébé or ewa in West Africa; is a warm-season, drought-tolerant food legume found throughout much of the semi-arid tropics. Cowpea, a member of the *Leguminosae* family, can be found growing in nearly every region of the tropics and subtropics but is an important food legume in much of semi-arid Africa. In many parts of Africa, cowpea exists as a critical source of dietary protein, often complimenting low-protein diets that typically consist of cereal and tubers like millet and cassava (Timko *et al.*, 2007). Scientists are uncertain of the crop's location of origin, but hypothesize that the crop may have originated in Western Africa, South Asia-Iran, or modern day Ethiopia (Kay, 1979). Today the largest portion of cowpea production occurs in Western Africa, with Nigeria being the leading producer of cowpea worldwide (Figure 3); in 2013 Nigeria produced 2.95 million tonnes of dried cowpeas (FAOSTAT, 2013b).

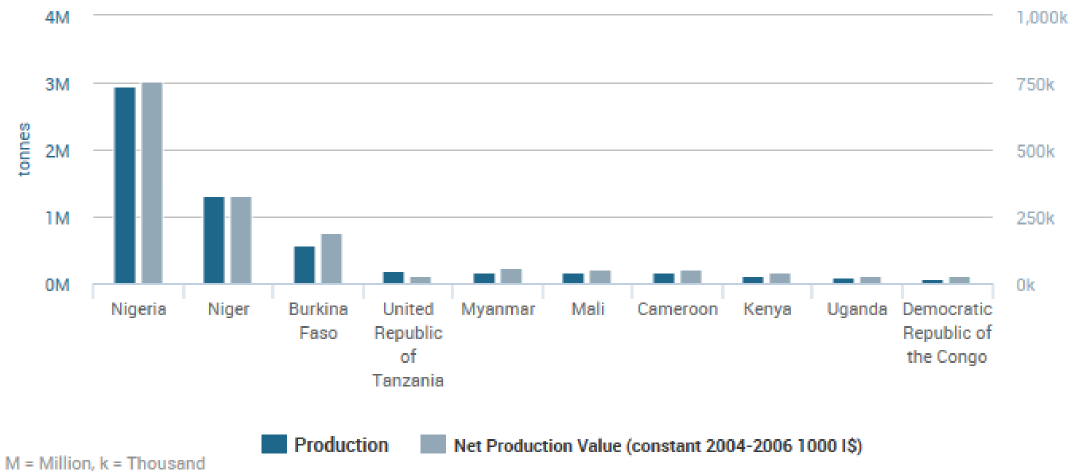


Figure 3. Top 10 Cowpea Producing Countries 2013 (FAOSTAT, 2013b).

Many varieties and variations of cowpea exist and include erect, semi-erect, trailing, and climbing types. The majority of these cowpea varieties are typically indeterminate, however many of the erect varieties are more often determinate types (Kay, 1979). Cowpea is consumed in a variety of ways in many countries, most commonly as a green or dried bean, but also as an immature pod (much like a snap bean), and even the young leaves are eaten and prepared like a spinach. Similar to the nutritional profile of other pulses, cowpea is relatively low in fat and has a protein content between two and four times that of a cereal or tuber crop (Timko *et al.*, 2007).

The nutritional composition of cowpea is similar to that of other edible legumes, with most of its nutritional value coming from protein and carbohydrates. Table 1 below illustrates the average nutritional components of cowpea of eight different cowpea varieties (Bressani, 1985).

	Cowpea
Protein	24.8%
Fat	1.9%
Fiber	6.3%
Carbohydrate	63.6%
Thiamine	0.00074%
Riboflavin	0.00042%
Niacin	0.00281%

Table 1. Basic Nutrient Content of Cowpea (Bressani, 1985)

Cowpea is an extremely drought tolerant crop and frequently does well in climates receiving less than 600mm a year. It has even been documented that in a Sahelian environment in West Africa, as much as 1000 kg/ha of dried grain was produced with as little as 181mm of rainfall (Hall and Patel, 1985). However it must be noted that plant productivity can be significantly reduced if moisture stress occurs during the period between emergence and first flowering (Kay, 1979).

In the Sahel region, cowpea is often grown in rotation with millet, sorghum, groundnuts, cassava, or maize. In many of the countries in this region, it is not uncommon to find cowpea grown in association with a variety of the aforementioned crops. Cowpea has been grown and experimented with in a number of different association techniques that include intercropping, relay cropping, and strip cropping. Researchers in these countries have also attempted to manipulate row and plant spacings, and have experimented with different morphological varieties of plants ranging from erect, semi-erect, trailing, and climbing types (Muleba and Ezumah, 1985).

Mungbean (*Vigna radiata* (L.) Wilczek)

Mungbean (*Vigna radiata* (L.) Wilczek) is an important grain legume crop in Asia, particularly India, and is commonly referred to as green gram, golden gram, oregon pea, chiroko, or simply mung (Duke, 1981). Mungbean typically complements cereal-based diets in regions of south-Asia by providing a reliable source of protein (Lambrides and Godwin, 2007). It is most commonly used in the sprouted form, and is one of the most widely used pulses in this manner. Mungbean is grown most extensively in India and ranks third among all pulses grown there; in 2001, 0.41 million tonnes were grown on 1.5 million hectares of land (Bains *et al.*, 2004). From there mungbean has since spread to South and East Asia, East and Central Africa, the West Indies, and into the United States (Akpapunam, 1996).

Mungbean is a short duration (55-110 days), warm season grain legume that grows especially well in the tropics and sub-tropics (Lambrides and Godwin, 2007). It is a drought tolerant crop that does well in places receiving anywhere from 700-900 mm of rainfall a year, and will grow well in temperatures anywhere in the range of $20^{o}C$ ($68^{o}F$) to $45^{o}C$ ($113^{o}F$) (Akpapunam, 1996). Mungbean will grow in soils ranging in pH from 4.3 to 8.1, but is typically susceptible to both waterlogging and salinity (Duke, 1981).

The mungbean plant grows in erect or semi-erect forms, depending on variety, and stands anywhere from 30 cm to 120 cm tall (Duke, 1981). Leaves are dark green and grow on long hairy petioles, with large leaflets that grow 5-10 cm long. Seeds pods are black, gray or brownish (2.5-10 cm long), and typically contain anywhere from 10 to 20 seeds. Seeds are usually green, but are capable of appearing olive, yellow, brown, or purplish-brown; they appear oblong and slightly flattened in shape, with a lightly colored hilum (Duke, 1981). In general appearance, the mungbean appears very similar to its counterpart, the black gram (Akpapunam, 1996).

Like other food legumes of the fabaceae family, mungbean is an excellent source of protein, vitamins, and minerals. On a dry-weight basis seeds contain 23-28% protein, 1-1.5% fat, 4.5% fiber, 60-65% carbohydrate, and a range of vitamins and minerals (Lambrides and Godwin, 2007). Table 2 below compares the nutritional makeups of cowpea and mungbean, values were pulled from the work of (Bressani, 1985) and (Lambrides and Godwin, 2007) respectively.

	Cowpea	**Mungbean**
Protein	24.8%	23.9%
Fat	1.9%	1.15%
Fiber	6.3%	16.3%
Carbohydrate	63.6%	62.6%
Thiamine	0.00074%	0.00062%
Riboflavin	0.00042%	0.00023%
Niacin	0.00281%	0.00251%

Table 2. Nutritional Comparison of Cowpea and Mungbean (Bressani, 1985) and (Lambrides and Godwin, 2007)

Dried seeds are used and consumed in a variety of ways; mungbean seeds are consumed in Asia whole or split, ground into flours, and even fermented into alcoholic beverages (Lambrides and Godwin, 2007). In the West, they are typically consumed as raw sprouts and used in salads. Raw sprouts have been found to contain (per 100 g): 30 calories, 4.2 g protein, 0.2 g fat, 0.9 g fiber and 5.0 total g of carbohydrates (Duke, 1981). Use of the crop is not limited to human consumption as it is sometimes used as a forage crop for livestock (Lambrides and Godwin, 2007).

Conservation Agriculture

Conservation agriculture, according to the UN Food and Agriculture Organization, consists of a set of basic agricultural principles applicable to all agricultural landscapes and land-uses and has been concisely defined as:

> "An approach to managing agro-ecosystems for improved and sustained productivity, increased profits and food security while preserving and enhancing the resource base and the environment (FAO, 2015)."

This approach is founded on the three core principles of conservation agriculture, sometimes referred to as the pillars of conservation agriculture (Reicosky and Saxton, 2006), which include (1) Continuous minimum mechanical soil disturbance, (2) Permanent organic soil cover, and (3) diversification of crop species grown in sequence and/or association (FAO, 2015). Conservation agriculture is not synonymous with organic agriculture, as it allows for the use of pesticides and synthetic fertilizers.

As of 2009 there were an estimated 100 million hectares of arable crops grown worldwide with no tillage in CA systems. However, this number remains small and only accounts for 6-7% relative to farms under conventional practices (Friedrich *et al.*, 2009). CA is practiced in all climatic zones of the world where crops are grown, and is adaptable to any size of farm. CA can be adapted to a ride array of soil types as well and has proven successful in soils with anywhere from 80% clay (Brazil) to soils around 90% sand (Australia) (Thierfelder and Wall, 2011).

Conservation Agriculture in the Sahel Region of West Africa

The practices of continuous minimum mechanical soil disturbance are more commonly referred to as conservation tillage, minimum tillage, no-tillage, or zero-tillage, and are typically used interchangeably and often incorrectly (Reicosky and Saxton, 2006). Many of the beneficial effects of reduced tillage practices go hand in hand with the subsequent maintenance of soil cover residues that result from having not disturbed the soil. While there are certain benefits that result almost exclusively from reduced soil disturbance and inversion, the majority of improvements are tied to the increases in soil organic matter that result from soil organic coverage.

Maintaining permanent organic soil cover in smallholder African farming systems is neither easy nor traditionally adhered to. Crop residues are generally burned, removed and used for fuel, livestock feed, or building materials (Bationo *et al.*, 1995). However, numerous studies have shown that the retention of crop residues has both short-term and long term benefits on a variety of soil properties and processes (Lahmar *et al.*, 2012) (Buerkert and Lamers, 1999). In recent years multiple studies have been conducted within an African context and have sought to understand these processes within African production systems (Lahmar *et al.*, 2012) (Buerkert and Lamers, 1999).

Soil Organic Matter (SOM)

One of the most obvious benefits of adopting conservation agriculture practices is the increase in soil organic matter build-up. Soil organic matter plays a vital role in the physical, chemical, and biological properties of soil and has at times even been referred to as ‘black gold’ (Reicosky and Saxton, 2006). Soil organic matter and humic substances are highly absorbent and typically act as cementing agents between soil particles, enabling increased soil aggregation and preventing slaking and dispersion (Ayanlaja and Sanwo, 1991). Well decomposed humus has been found to contain much greater cation exchange capacities than typical soil colloids, with as much as 300 meq/100g humus. Clay components such as kaolinite may only contain 3-

15 meq, while illite and montmorillonite may contain 30-40 and 80-150 meq respectively (Vaughan and Malcolm, 1985). The presence of SOM and humus become especially vital in regions of West Africa where fine clays and colloidal fractions are sparse. Soil organic matter becomes the primary source in the soil's ability to retain nutrients and water (Ayanlaja and Sanwo, 1991). In many tropical regions of the world soils contain very low levels of inorganic nutrients, and thus rely on the recycling of nutrients gained from organic matter (Tiessen *et al.*, 1994).

Soil organic matter is also linked to microbial activity in soils, which tend to be good indicators soil fertility, or lack thereof (Troeh and Thompson, 2005). Organic residues of plant and animal waste are the parent materials of organic matter and humus, which make up the nutrient supplies of microorganisms. Microbial activity plays an important role in the release of plant nutrients from dead materials, and without this process, soil nutrients would soon be used up (Troeh and Thompson, 2005).

Soil Moisture

As is the case in any rain-fed agricultural setting, moisture conservation in the West African Sahel is of the utmost importance. This absolute need to conserve soil moisture and prevent further water losses have led to much research in this area. Researchers are in relative agreement that the maintenance of permanent organic soil cover offered by CA practices (such as a live cover crop, the retention of crop residues, or the addition of organic mulches) does improve soil moisture conservation (Lal, 1974) (Lahmar *et al.*, 2012).

The effects of mulch on soil moisture were examined by Ramakrishna *et al*. (2006) and showed significant improvements over bare control plots. Soil moisture effects were compared using three different mulch treatments; these included (1) a straw mulch, (2) a polythene mulch, and (3) a chemical mulch. Use of straw mulch significantly decreased the rates of evaporation from the soil compared to unmulched control plots. Moisture differences between mulched and unmulched plots ranged from 10% to 22% only a few days after rainfall events (Ramakrishna *et al.*, 2006). In a similar study conducted in Nigeria by Lal (1974), mulched plots maintained higher moisture contents throughout the growing season when compared to unmulched plots. It was concluded that mulch improved soil moisture storage over short periods of drought (Lal, 1974).

Intercropping

Intercropping can be defined as the growing of various combinations of crops, trees and pasture species simultaneously in the same field, in the same year (Sinoquet, 1995). Much research has been focused on this topic in recent years as scientists seek to understand the potential benefits of such cropping systems. Intercropping of different crops provides a variety of added benefits to the cropping system, including more insurance against single crop failures, greater yields of organic matter, and the ability to harvest different crops at different times.

In one experiment done in New York state, researchers explored some of the benefits of intercropping systems in comparison to conventional monocropping systems (Innis, 1997) and found convincing results. Using equal sized plots, Innis (1997) found that monocropped maize and monocropped beans produced higher yields than when intercropped together, but found that intercropping the two yielded higher amounts of food overall. In terms of each system's Land Equivalent Ratio (LER), Innis (1997) came up with the following results: intercropped beans produced 0.69 of the yield of monocropped beans, while intercropped maize produced 0.66 of the yield of monocropped maize. However, combining the two intercropped yields resulted in an LER of 1.35, meaning that the same sources of water, sun, and nutrients produced 35% more than when monocropped (Innis, 1997). Similar results were found in experiments with rice and various intercrops (soybean, peanut, mungbean) in India (Mandal *et al.*, 1990). Depending on production environment, intercropping may or may not be ideal. If the desired outcome is the maximization of the primary crop's yield, then intercropping might take away from said goals. On the other hand, if the desired outcome is greater food security through overall yields, the insurance of a second crop, and organic matter build-up, then intercropping may be a viable solution.

Intercropping Millet and Cowpea in Senegal

In most regions of Senegal, millet is typically grown in monoculture and rotated periodically with peanut or cowpea. There are regions of Senegal, such as the northern part of the country, where farmers are known to intercrop millet with cowpea on a regular basis. Unfortunately, very few studies have been conducted within this region. Several studies have attempted to assess the overall potential for intercropping millet and cowpea, but most of these studies have been located in other West African countries such as Niger and Nigeria (Bielders *et al.*, 2002, Ntare, 1990, Reddy *et al.*, 1992, Sivakumar, 1993). Very few studies have sought to assess the potential for intercropping cowpea and millet within a Senegalese context.

Many of the related studies located in Senegal focused on millet grown in rotation with cowpea, but not necessarily intercropped with cowpea. There have been a few studies conducted in Senegal pertaining to millet-cowpea intercropping, but these studies are fewer in number. A similar study to our study was conducted to assess several morphologically different varieties of cowpea intercropped with millet (Thiaw *et al.*, 1993), however this research did not attempt to quantify ground cover increase as it relates to soil moisture retention and yield.

References

Akpapunam, M. 1996. Mungbean (*Vigna radiata* (L.) Wilczek). In: E. Nwokolo and J. Smartt, editors, Food and Feed from Legumes and Oilseeds. Chapman & Hall, London, UK. p. 209-215.

Amblard, S. and J. Pernes. 1989. The identification of the cultivated pearl millet (*Pennisetum*) amongst plant impressions on pottery from Oued Chebbi (Dhar Oualata, Mauritania). . Afr Archaeol Rev: 117-126.

Andrews, D.J., J. Rajewski and A. Kumar. 1993. Pearl Millet: New feed Grain Crop. In: J. Janick and J. E. Simons, editors, New Crops. Wiley, New York. p. 198-208.

Athwal, D.S. 1966. Current Plant Breeding Research with Special Reference to Pennisetum. Indian J. Genet. Plant Breed.: 73-85.

Ayanlaja, S.A. and J.O. Sanwo. 1991. Management of soil organic matter in the farming systems of the low land humid tropics of West Africa: a review. Soil Technology 4: 265-279.

Bains, T.S., J.S. Brar, G. Singh, H.S. Sekhon and B.S. Kooner. 2004. Status of Production and Distribution of Mungbean Seed in Different Cropping Seasons. In: S. Shanmugasundaram, editor Improving Income and Nutrition by Incorporating Mungbean in Cereal Fallows in the Indo-Gangetic Plains of South Asia. The World Vegetable Center AVRDC, Taiwan. p. 104-115.

Bationo, A., A. Buerkert, M. Sedogo, C.B. Christianson and M. A. 1995. A Critical Review of Crop-Residue use as a Soil Amendment in the West African Semi-Arid Tropics. Sustainable Nutrient Cycling in Mixed Farming Systems of Sub-Saharan Africa. Internationa Livestock Centre for Africa, Addia Ababa, Ethiopia.

Bationo, A., C.B. Christianson and M.C. Klaij. 1993. The effect of crop residue and fertilizer use on pearl millet yields in Niger. Fertilizer Research 34: 251-258.

Bielders, C.L., K. Michels and A. Bationo. 2002. On-farm evaluation of ridging and residue management options in a Sahelian millet-cowpea intercrop. 1. Soil quality changes. Soil Use and Management 18: 216-222.

Bressani, R. 1985. Nutritive Value of Cowpea. In: S. R. Singh and K. O. Rachie, editors, Cowpea Research, Production and Utilization. John Wiley & Sons Ltd., U.K. p. 353-359.

Buerkert, A. and J. Lamers. 1999. Soil erosion and deposition effects on surface characteristics and pearl millet growth in the West African Sahel. Plant Soil: 239-253.

Dendy, D.A.V. 1995. Sorghum and Millets: Production and ImportanceAmerican Association of General Chemists, St Paul, MN.

Devos, K., W. Hanna and P. Ozias-Akins. 2006. Pearl Millet. In: C. Kole, editor Cereals and Millets. Springer Berlin Heidelberg. p. 303-323.

Duke, J.A. 1981. Handbook of Legumes of World Economic Importance Plenum Press, New York.

FAO. 2015. What is Conservation Agriculture? United Nations Food and Agriculture Organization - Agriculture and Consumer Protection Department. http://www.fao.org/ag/ca/1a.html (accessed 10 Feb. 2015.)

FAOSTAT. 1996. The world sorghum and millet economies: facts, trends and outlook. Economic and Social Development Department. http://www.fao.org/docrep/W1808E/w1808e0l.htm#TopOfPage (accessed 05 Dec. 2014.)

FAOSTAT. 2012. Worldwide grain production rankings. Food and Agriculture Organization of the United Nations - Satistics Division. http://faostat3.fao.org/browse/rankings/commodities_by_regions/E (accessed 10 Feb. 2015.)

FAOSTAT. 2013a. Millet Production Senegal. United Nations Food and Agriculture Organization - Division of Statistics. http://faostat3.fao.org/browse/rankings/commodities_by_country/E (accessed 10 Feb. 2015.)

FAOSTAT. 2013b. Top 10 Cowpea Producing Countries 2013. United Nations Food and Agriculture Organization - Division of Statistics. http://faostat3.fao.org/browse/rankings/countries_by_commodity/E (accessed 10 Feb. 2015.)

FAOSTAT. 2013c. Top 10 Food and Agricultural Commodities Produced in Senegal in 2013. United Nations Food and Agriculture Organization - Division of Statistics. http://faostat3.fao.org/browse/rankings/commodities_by_country/E (accessed 10 Feb. 2015.)

FAOSTAT. 2013d. Top 10 Millet Producing Countries 2013. United Nation Food and Agriculture Organization - Division of Statistics. http://faostat3.fao.org/browse/rankings/countries_by_commodity/E (accessed 10 Feb. 2015.)

Friedrich, T., A. Kassam and F. Shaxon. 2009. Conservation Agriculture. Conservation Agriculture Crop Bioengineering Challenges for Tropical Agriculture.

Fussell, L.K., M.C. Klaij, C. Renard and B. N'Tare. 1989. Millet based production systems for improving food production in the southern Sahelian zone. Farming Systems Research Workshop on Appropriate Technologies for Achieving Sustainable Food Production Systems in Semi-Arid Africa. Ouagadougou, Burkina Faso.

Germplasm Resources Information Network. 2009. GRIN Taxonomy for Plants. USDA Agricultural Research Service, Beltsville, MD. http://www.ars-grin.gov/cgi-bin/npgs/html/taxon.pl?27187 (accessed 10 Feb. 2015.)

Grove, A.T. 1978. Geographical Introduction to the Sahel. The Geographical Journal 144: 407-415.

Hall, A.E. and P.N. Patel. 1985. Breeding for Resistance to Drought and Heat. In: S. R. Singh and K. O. Rachie, editors, Cowpea Research, Production, and Utilization. Wiley, New York. p. 137-151.

Harlan, J.R. 1971. Agricultural Origins: Centers and Non-Centers. Science 174: 468-474.

Hart, R.H. and G.W. Burton. 1965. Effect of Row Spacing, Seeding Rate and Nitrogen Fertilizeration on Forage and Yield Quality of Gahi-1 Pearl Millet. Agron. J.: 376-378.

Hoogmoed, W.B. and L. Stroosnijder. 1984. Crust formation on sandy soils in the Sahel I. Rainfall and infiltration. Soil and Tillage Research 4: 5-23.

Hulse, J.H., E. Laing and O. Pearson. 1980. Sorghum and the Millets: Their Composition and Nutritive ValueAcademic Press Inc, New York, NY.

Innis, D.Q. 1997. Intercropping and the Scientific Basis of Traditional AgricultureIntermediate Technology Publications, Ltd., London, UK.

Kassam, A.H. and J.M. Kowal. 1975. Water use, energy balance and growth of gero millet at Samaru, Northern Nigeria. Agr. Met.: 333-342.

Kay, D.E. 1979. Food Legumes.Tropical Products Institute, Gray's Inn Road London.
L'Hôte, Y., G.I.L. Mahe, B. Some and J.P. Triboulet. 2002. Analysis of a Sahelian annual rainfall index from 1896 to 2000; the drought continues. Hydrological Sciences Journal 47: 563-572.

Lahmar, R., B.A. Bationo, N. Dan Lamso, Y. Guéro and P. Tittonell. 2012. Tailoring conservation agriculture technologies to West Africa semi-arid zones: Building on traditional local practices for soil restoration. Field Crops Res. 132: 158-167.

Lahmar, R., B.A. Bationo, N.D. Lamso, Y. Guéro and P. Tittonell. 2012. Tailoring conservation agriculture technologies to West Africa semi-arid zones: building on traditional local practices for soil restoration. Field Crops Res. 132: 158-167.

Lal, R. 1974. Soil temperature, soil moisture and maize yield from mulched and unmulched tropical soils. Plant Soil 40: 129-143.

Lambrides, C.J. and I.D. Godwin. 2007. Mungbean. In: C. Kole, editor Pulses, Sugar and Tuber Crops. Springer, Hedeilberg, Germany. p. 69-90.

Mandal, B.K., M. Dhara, B. Mandal, S. Das and R. Nandy. 1990. Rice, Mungbean, Soybean, Peanut, Ricebean, and Blackgram Yields under Different Intercropping Systems. Agron. J. 82: 1063-1066.

Manning, K., R. Pelling, T. Higham, J.-L. Schwenniger and D.Q. Fuller. 2011. 4500-Year old domesticated pearl millet (Pennisetum glaucum) from the Tilemsi Valley, Mali: new insights into an alternative cereal domestication pathway. Journal of Archaeological Science 38: 312-322.

Matlon, P.J. 1987. The West African Semiarid Tropics. Accelerating food production in sub-Saharan Africa. ICRISAT, Victoria Falls, Zimbabwe.

Muchow, R.C. 1989. Comparative productivity of maize, sorghum and pearl millet in a semi-arid tropical environment I. Yield potential. Field Crops Res. 20: 191-205.

Muleba, N. and H.C. Ezumah. 1985. Optimizing Cultural Practices for Cowpea in Africa. In: S. R. Singh and K. O. Rachie, editors, Cowpea Research, Production and Utilization. John Wiley & Sons Ltd., U.K. p. 289-295.

Ntare, B.R. 1990. Intercropping Morphologically Different Cowpeas With Pearl Millet in a Short Season Environment in the Sahel. Exp. Agric. 26: 41-47.

Rachie, K.O. and J.V. Majmudar. 1980. Pearl MilletThe Pennsylvania State University Press, University Park, PA.

Ramakrishna, A., H.M. Tam, S.P. Wani and T.D. Long. 2006. Effect of mulch on soil temperature, moisture, weed infestation and yield of groundnut in northern Vietnam. Field Crops Res. 95: 115-125.

Reddy, K.C., P. Visser and P. Buckner. 1992. Pearl millet and cowpea yields in sole and intercrop systems, and their after-effects on soil and crop productivity. Field Crops Res. 28: 315-326.

Reicosky, D.C. and K.E. Saxton. 2006. The Benefits of No-Tillage. In: C. J. Baker, K. E. Saxton, W. R. Ritchie, W. C. T. Chamen, D. C. Reicosky, M. F. Ribeiro , S. E. Justice and P. R. Hobbs, editors, No-tillage seeding in conservation agriculture. USDA - ARS, Morris, MN.

Sinclair, A.R.E. and J.M. Fryxell. 1985. The Sahel of Africa: ecology of a disaster. Canadian Journal of Zoology 63: 987-994.

Sinoquet, H. 1995. Foreword. In: H. Sinoquet and p. Cruz, editors, Ecophysiology of Tropical Intercropping. Institut National De La Recherche Agronomique, Paris.

Sivakumar, M.V.K. 1993. Growth and Yield of Millet and Cowpea in Relay and Intercrop Systems in the Sahelian Zone in Years when the Onset of the Rainy Season is Early. Exp. Agric. 29: 417-427.

Stoskopf, N.C. 1985. Pearl Millet. Cereal Grain Crops. Reston Publishing Company, Inc., Reston, Virginia. p. 429-444.

Thiaw, S., A.E. Hall and D.R. Parker. 1993. Varietal intercropping and the yields and stability of cowpea production in semiarid Senegal. Field Crops Res. 33: 217-233.

Thierfelder, C. and P.C. Wall. 2011. Reducing the Risk of Crop Failure for Smallholder Farmers in Africa Through the Adoption of Conservation Agriculture. In: A. Bationo, B. Waswa, J. M. Okeyo, F. Maina and J. M. Kihara, editors, Innovations as Key to the Green Revolution in Africa. Springer Netherlands. p. 1269-1277.

Tiessen, H., E. Cuevas and P. Chacon. 1994. The role of soil organic matter in sustaining soil fertility. Nature 371: 783-785.

Timko, M.P., J.D. Ehlers and P.A. Roberts. 2007. Cowpea. In: C. Kole, editor Pulses, Sugar and Tuber Crops. Springer, Hedeilberg, Germany. p. 49-63.

Troeh, F.R. and L.M. Thompson. 2005. Soils and Soil Fertility. 6th ed. Blackwell Publishing, Ames, Iowa.

UNDATA. 2013. World Statistics Pocketbook - Senegal Profile. United Nations Statistics Division. http://data.un.org/CountryProfile.aspx?crName=SENEGAL (accessed 10 Feb. 2015.)

Vaughan, D. and R.E. Malcolm, editor. 1985. Soil organic matter and biological activity. Martinus Nijhoff/Dr W. Junk Publishers, Dordrecht, The Netherlands.

Vidal, P. 1962. Influence des facteurs pédoclimatiques sur la nutrition et la production des mils *Pennisetum* cultivés au Sénégal (Influence of pedoclimatic factors on nutrition and production of *Pennisetum* millet cultivated in senegal 1962). Colloque CCTA/FAO sur les Céréales des Zones de Savane. Dakar.

Chapter III: Conservation agriculture in Senegal: comparing the effects of intercropping and mulching on millet yields

Abstract

Situated on the western edge of Africa's harsh Sahel region, Senegal faces a number of agricultural production constraints. Limited rainfall, poor soil fertility, and insufficient agronomic inputs all contribute to low yielding millet production systems. This study was initiated to assess the potential for intercropping either cowpea (*Vigna unguiculata* (L.) Walp.) or mungbean (*Vigna radiata* (L.) Wilczek) into traditional pearl millet (*Pennisetum glaucum* (L.) R. Br.) cropping systems. During the 2013 and 2014 growing seasons two varieties of cowpea (upright and viney), and one variety of mungbean (upright) were grown in monoculture and subsequently intercropped with millet to evaluate the potential for increasing millet and overall yields. Millet was also planted with a mulch (2 t/ha of neem leaves) to test the effectiveness of increased ground cover on millet yields. In addition to yield data, soil moisture and plant NDVI data were also collected. Millet grain yields increased when intercropped with either cowpea or mungbean compared to millet that was grown alone, with grain yield increases of up to 55%. Additionally, the combined grain yields (millet + bean) were up to 67% higher than the traditional monoculture millet. The addition of mulch was the most effective treatment and increased millet grain yields up to 70%. Soil moisture increased up to 14% in mulched treatments over millet monoculture treatments. All yield increases were achieved without the addition of fertilizers or nutrient amendments. In an attempt to mimic local practices our experiment was rainfed and no soil amendments were introduced.

Introduction

Senegal is home to one of West Africa's most stable economies, but like many countries in the region it continues to struggle to provide for the daily caloric needs of a growing population. The combination of population growth, small land holdings, lack of adequate agronomic inputs, and the environmental stresses of the region, have all combined to leave Senegalese subsistence farmers struggling to produce enough food. Located on the western edge of Africa's vast Sahel region, Senegal experiences some of the harshest row-cropping conditions in Africa. Senegal's central millet-groundnut basin receives as little as 250-750 mm of rainfall in an average year, and has a typical growing season of 90 days or less (Fussell *et al.*, 1989). Poor fertility, low water-holding capacity, and little to no organic matter are typical of the sandy soils found in this region of Senegal (Fofana *et al.*, 2008).

In response to these harsh conditions, many smallholder subsistence farmers in this region choose to cultivate a combination of drought tolerant crops that include pearl millet, sorghum, cowpea, and groundnut. These crops are most commonly grown in rotation with each other, and to a lesser extent, are intercropped in various combinations. Though not as common as traditional rotational systems, cereal legume intercropping systems have great potential in the region for enhancing food security. Millet-cowpea intercropping is one of the combinations more widely practiced in the region and is often adopted as an insurance tactic, allowing farmers to spread the risk of crop failure across two crops (Bationo and Ntare, 2000).

The most widely grown cereal crop in the region is pearl millet (*Pennisetum glaucum* (L.) R. Br.), which is well adapted to growing conditions that are not suited for other crops such as maize (*Zea mays* L.). It is well suited for growing in soils that are too sandy, too dry, and too infertile for other grain crops such as maize and sorghum (Stoskopf, 1985). Unfortunately in

Senegal, millet production continues to fall short of its potential year after year. According to the United Nations Food and Agriculture Organization, Senegal yielded a yearly average of 770 kg/ha of millet grain over the past 20 years, compared to a West African average of 662 kg/ha and an Indian average of 898 kg/ha (FAOSTAT, 2013). More importantly, Senegal's 770 kg/ha average has hardly improved since the 1970's and has remained essentially stagnant while other crops such as rice, maize, and cassava have all experienced yield increases (FAOSTAT, 2013).

In Senegal, pearl millet is considered a low-value crop grown for household consumption, and therefore does not receive the additional inputs (when available) that might be otherwise invested into cash-crops like groundnuts or vegetable crops. There is a crucial need to boost millet yields in ways that are affordable and accessible to the average smallholder farmer of Senegal's central millet-groundnut basin. Production practices that have the potential to build soil health without the introduction of external resources could prove to be critical in this region. Research conducted in several African countries and beyond, indicates significant yield improvements when the principles of conservation agriculture have been practiced (Buerkert and Lamers, 1999, Lahmar *et al.*, 2012). Conservation agriculture, which relies on the three basic tenants of (1) crop diversification, (2) continuous ground cover, and (3) minimum tillage, has every potential to be adopted by the average smallholder farmer in Senegal (FAO, 2015).

During the 2013 and 2014 growing seasons, field studies were conducted in two locations in central Senegal to assess the potential for improving pearl millet yields without having to introduce any external inputs such as fertilizers or irrigation systems. The study specifically aims to assess the potential for improving millet yields through the introduction of a suite of conservation agriculture practices tailored to the region. The objectives of our study were to evaluate (1) the effects of intercropping vs. monocropping on grain yields, (2) the potential for intercropping cowpea or mungbean between millet rows without driving down millet yields, (3) the use of intercropping and mulching practices (through increased ground cover) as a means to improving soil moisture retention, and (4) mungbean as a potential alternative to cowpea in Senegal's millet-cowpea systems.

Materials and Methods

Site Description

Field studies were established at two sites within Senegal's central millet-groundnut basin during the growing seasons of 2013 and 2014. The research sites were located on the campuses of the École Nationale Supérieur d'Agriculture (14°45'45 N, 16°53'14 W) near the city of Thiés, and the Institut Supérieur de Formation Agricole et Rurale (14°41'38 N, 16°28'12 W) near the city of Bambey. The climate in this region of Senegal is characterized by a short unimodal rainy season that typically occurs between June and October (Figure 4).

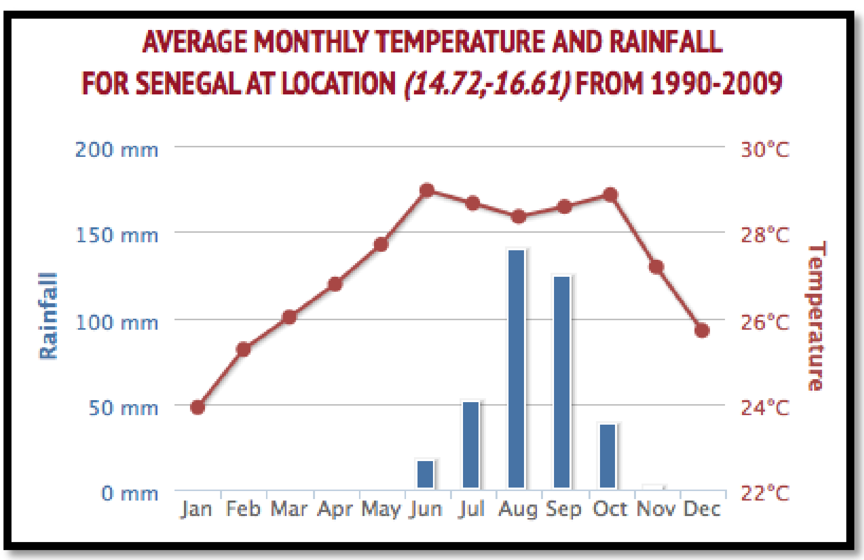


Figure 4. Average monthly rainfall (mm) and temperature (oC) in the Thiés region (The Climate Research Unit of East Anglia, 2014)

Average annual rainfall (1990-2009) in this area is approximately 300mm and the mean monthly temperature is 27°C-29°C (Figure 4). The onset of rain in 2014 (August 5) was unseasonably late, and resulted in a very short growing season (~80 days) compared with the 2013 growing season. Soils at both sites are typical of the region and soil tests of the two sites are summarized below (Table 3).

Site	pH (1:2.5)	Carbon (%)	CEC (meq/100g)	Soil Composition (%)		
				Sand	Silt	Clay
Bambey	6.69	0.59	5.3	86.3	6.0	7.7
Thiés	7.45	0.28	6.7	82.3	12.1	5.6

Table 3. Soil properties at Bambey and Thies

Experimental Details

The experiment consisted of eight treatments arranged in a Randomized Complete Block Design (RCBD) with four replications (blocks) (Table 4). The experiment included two morphologically different varieties of cowpea (*Vigna unguiculata* (L.) Walp.), and one variety of mungbean (*Vigna radiata* (L.) Wilczek). Each bean variety was grown in monoculture, and intercropped with pearl millet (*Pennisetum glaucum* (L.) R. Br.). Millet was also grown alone according to local practice, with and without mulch. Local varieties were used for each cowpea treatment, and were obtained from Senegal's plant breeding institute ISRA (Institut Sénégalais de Recherches Agricoles). Cowpea and mungbean seeds were inoculated prior to planting with appropriate rhizobacteria. Neem (*Azadirachta indica*) leaves were used as mulch in treatment eight (applied at 2 t/ha), and were harvested on location at each of the sites. Neem was selected as an appropriate mulch due to its abundance and local availability throughout Senegal, and its potential as an appropriate mulch (Tilander and Bonzi, 1997).

	Treatment	Variety
1.	Millet Sole	(Millet) ISMI-9507
2.	Millet – Cowpea (Viney) Intercrop	(Millet) ISMI-9507 – (Cowpea) Melakh
3.	Millet – Cowpea (Upright) Intercrop	(Millet) ISMI-9507 – (Cowpea) Yacine
4.	Millet – Mungbean Intercrop	(Millet) ISMI-9507 – (Mungbean) Berkens
5.	Cowpea (Viney) Sole	(Cowpea) Melakh
6.	Cowpea (Upright) Sole	(Cowpea) Yacine
7.	Mungbean Sole	(Mungbean) Berkens
8.	Millet with Mulch	(Millet) ISMI-9507 - (Mulch) Neem

Table 4. List of treatments and specific varieties used in each treatment

Individual plots measured 4m by 4m. Millet was planted in hills and thinned to 3 plants per hill; hills were spaced 1m x 1m with plant densities of 10,000 pockets per hectare. Beans were planted at 0.5m x 0.5m and thinned to 1 plant per pocket. Plant densities were 40,000 pockets per hectare for monoculture beans and 20,000 pockets per hectare for intercropped beans. Planting densities were based on recommendations from local Senegalese researchers at the Institut Sénégalais de Recherches Agricoles (ISRA). Plant density was decreased by 50% from its original monocropping practice in the intercropping treatments (Figure 5). The experimental sites had been left fallow the season prior and were disked before planting in 2013. Both sites were left untilled in 2014 and crops were planted manually into the previous year's crop residue. Between-row weeding was done three times in the beginning of each season with a draft-powered (horse) cultivator and manually with a hoe.

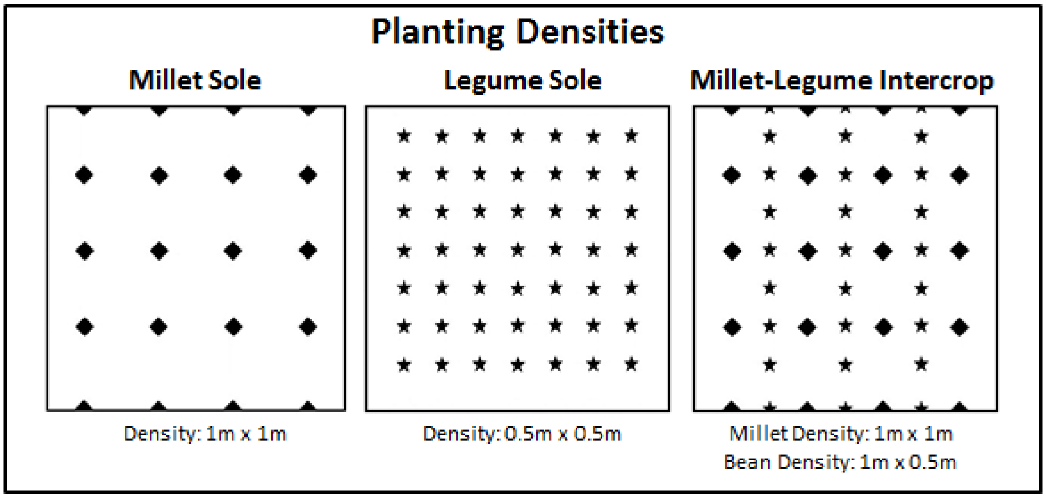


Figure 5. Planting arrangements for millet sole, cowpea & mungbean sole, and millet-bean intercropping treatments.

Data Collection

Millet was manually harvested from the two inside rows (4m rows) of each plot and grain was dried and yields were calculated based on 12.5% moisture content. Beans were left on the plant to dry and harvested from inside rows (4m rows); each plant was harvested weekly until all mature pods were collected. Cowpea and mungbean grain yield calculations were also based on 12.5% moisture content. In addition to millet grain yield, number of panicles and average panicle length were measured and recorded at harvest. For beans, the number of total pods was recorded. Soil moisture readings were taken daily using a FieldScout TDR 100 soil moisture meter (Spectrum Technologies, Inc., Plainfield, IL). Three readings were randomly recorded from each plot in the two middle blocks. The TDR probes were calibrated to the soils at each site to ensure accurate results. Normalized Difference Vegetation Index (NDVI) readings were collected every two weeks in each plot. NDVI readings were recorded using a Trimble Greenseeker™ hand-held optical sensor (Trimble Navigation, Sunnyvale, CA) and millet and beans were measured separately.

Table 5 summarizes the planting, weeding, thinning, and harvesting dates for the 2013 and 2014 growing seasons. All crops were grown under rain-fed conditions with no fertilizer, insecticide, or herbicide inputs.

	2013		**2014**	
	Bambey	Thiès	Bambey	Thiès
Planting	July 17	July 15	August 7	August 6
Weeding	July 27; Aug. 6, 16	July 25; Aug. 4, 15	Aug. 17, 27; Sept. 4	Aug. 16, 25; Sept. 4
Thinning	August 7	August 5	Aug. 28	Aug. 26
Cowpea Harvest	Sept. 17 – Oct. 1	Sept. 19 – Oct. 3	Oct. 01 - 22	Oct. 01 - 19
Millet Harvest	October 9	October 7	October 23	October 22

*Thinning was done 3 weeks after planting.

Table 5. Timetable of management practices for field trials at Bambey and Thiés

Data Analysis

Yield data were analyzed using analysis of variance (ANOVA) (SAS Institute Inc., Cary, NC). Fisher's LSD was used to analyze means separation between treatments. Contrasts were used to examine statistical differences between millet monocropping treatments and the average of the three intercropping treatments. A covariate was used in the analysis of the bean yield data to account for plant population differences in individual plots. An alpha level of 0.05 was used in all statistical analyses to determine significant differences among treatments.

Environmental Conditions

The timing of the rainy season in 2013 was similar to previous years, with rains commencing in the middle of July and continuing until the middle of October. Compared to the previous several years, the amount of rainfall received during the 2013 growing season was above average. In 2013 Bambey and Thiès received 638 mm and 465 mm of rainfall, with 49 and 39 days of rain, respectively. In 2014 the rainy season did not begin until the first week of August, almost a month later than 2013. However, rainfall continued into mid-October and fell regularly and consistently. Total rainfall was 419 mm and 331 mm at Bambey and Thiès, respectively. Although the amount of rain received between the two sites differed across the two seasons, days of rain between sites over years did not differ greatly (Figure 6). Millet was harvested after 82 days in 2013 and 79 days in 2014.

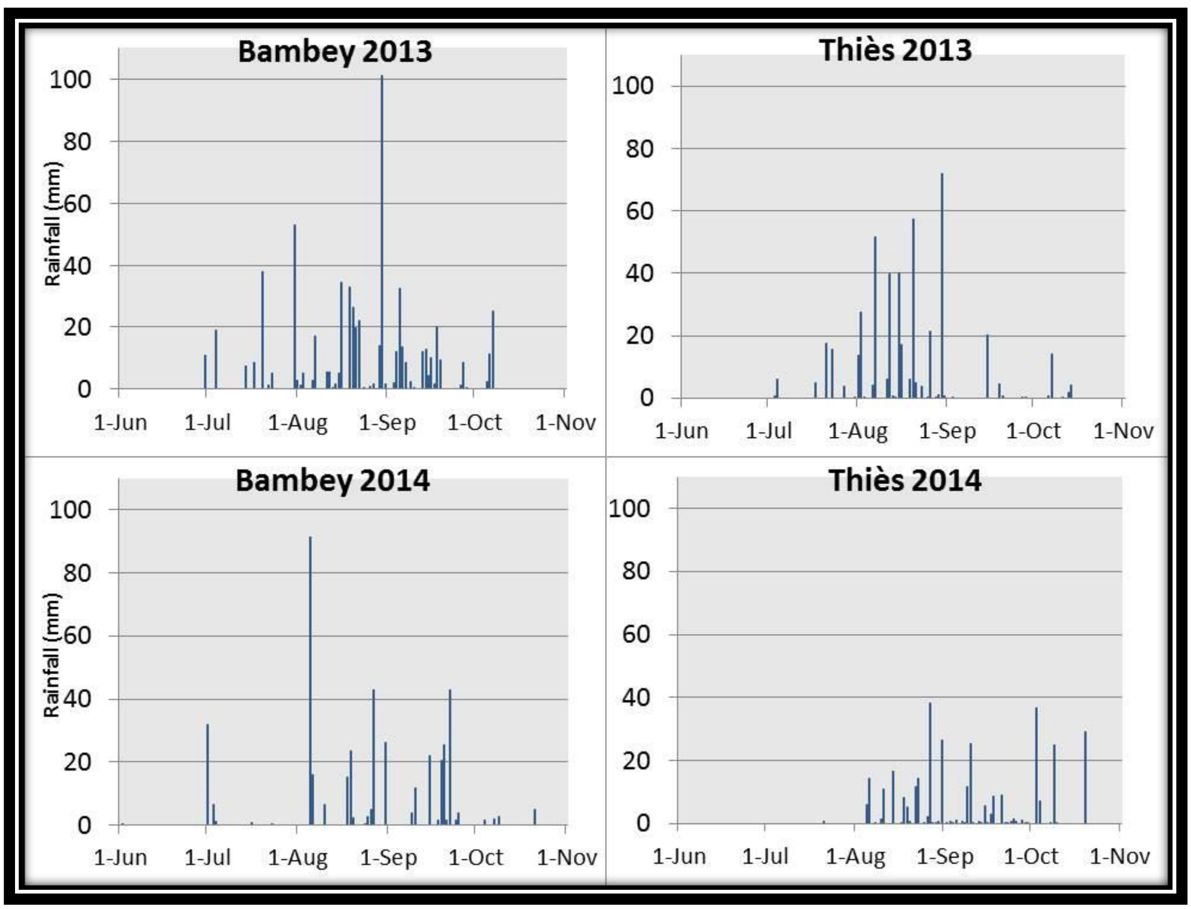


Figure 6. Daily rainfall data for 2013 and 2014 growing seasons at Bambey and Thiés.

Results

Millet, bean, and combined intercropping yields

Table 6 below summarizes the overall Analysis of Variance (ANOVA) for dependent variables in the study. Although there were no significant differences in grain yield between sites and years for millet grain yield, there was a site by treatment interaction, indicating that treatment outcomes differed between sites. Consequently, we will present grain yield separately for sites, but averaged across years.

		Millet			Bean		Combined	
Source	Df	Millet Yield (kg/ha)	Panicle Count	Panicle Length (cm)	Bean Yield (kg/ha)	Pod Count	Combined Yield (kg/ha)	LER
Site	1	ns	ns	ns	**	***	ns	**
Year	1	ns	ns	*	ns	ns	ns	ns
Treatment	7	***	***	***	***	***	***	***
Site x Year	1	ns	**	ns	***	***	ns	ns
Site x Treatment	7	*	ns	*	***	***	**	**
Year x Treatment	7	ns	ns	ns	ns	ns	ns	ns
Site x Year x Treatment	7	ns	ns	ns	*	ns	ns	ns
Block(Site x Year)	12	**	ns	ns	ns	*	***	**
Model	43							
Error	84							
Total	127							

ns= non-significant   * = $p < 0.05$ ** = $p < 0.01$ *** = $p < 0.001$

Table 6. ANOVA of main effects (site, year, treatment, and block) and interactions on response of millet, bean, and intercrops

Despite the late onset of rain and a shorter growing season in 2014, average millet yields did not differ significantly from 2013. Although rainfall varied across years, frequency of rainfall was similar across years. Thus, despite the fact that the onset of rain was delayed by over a month in 2014, average millet yields were slightly higher in 2014 compared to 2013. The difference in millet yield was small with yields averaging 2027 kg/ha and 1925 kg/ha for 2014 and 2013, respectively.

Millet intercropped with cowpea or mungbean almost always yielded more than the millet grown in monoculture. With the exception of the millet intercropped with the viney cowpea in Thiès, all of the intercropping and mulching treatments yielded more than the millet grown in monoculture (Figure 7).

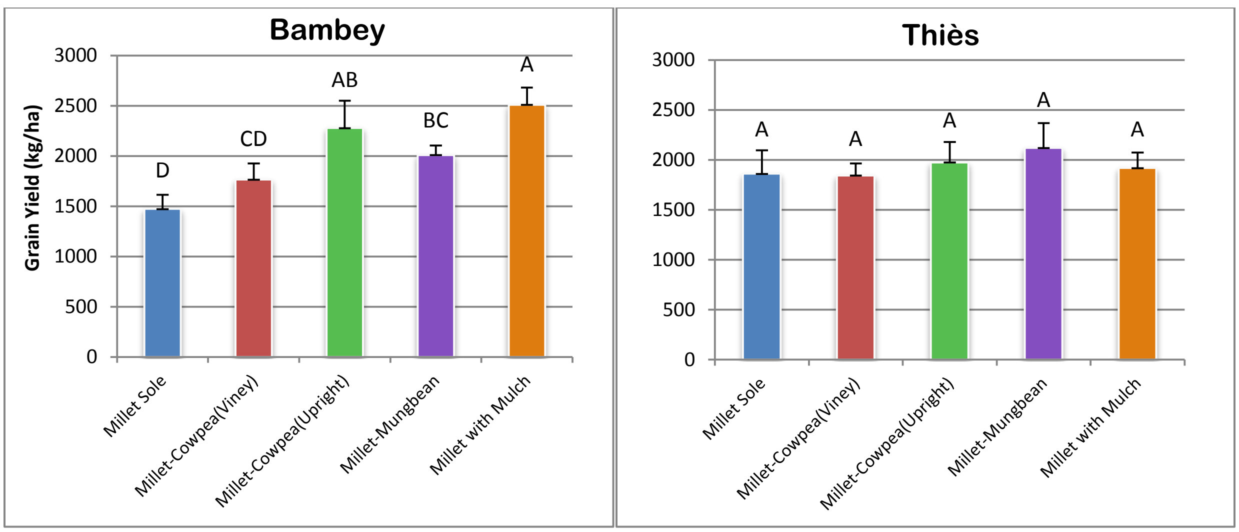


Figure 7. Millet grain yield at Bambey and Thiès, averaged across 2013 and 2014. Treatments with the same letter are not significantly different from each other at alpha=0.05 (Fisher's LSD) and error bars were constructed using 1 standard error from the mean.

In Bambey, millet grown alone yielded 1473 kg/ha compared with 1766, 2279, and 2009 kg/ha for millet intercropped with the viney cowpea, upright cowpea, and mungbean, respectively. The percent yield increases between millet grown alone and intercropped millet were 20%, 55%, and 36% for the millet-viney cowpea, millet-upright cowpea, and mungbean treatments, respectively. Millet grown with mulch yielded the highest at 2510 kg/ha, a yield increase of 70% compared to millet grown in monoculture. Differences among treatments were not significant in Thiès. With the exception of the millet that was intercropped with the viney cowpea variety, yields of intercropped millet did not fall below that of the millet grown in monoculture.

Similar to millet yield, bean yield did not differ across years. However, there were differences between sites, and treatment differences were observed at each site. There were significant site by treatment interactions and site by year interactions (Table 6), thus the bean yield data are reported separately across sites and treatments.

The effect of year on bean yield differed between locations (Figure 8). Bean yield was higher in 2013 and lower in 2014 at the Bambey location while the opposite was true at the Thiès location (Figure 8). Bean yield also differed across locations (Figure 9) with mungbean, for example, showing a much lower yield at the Bambey site compared to that of Thiès (Figure 9).

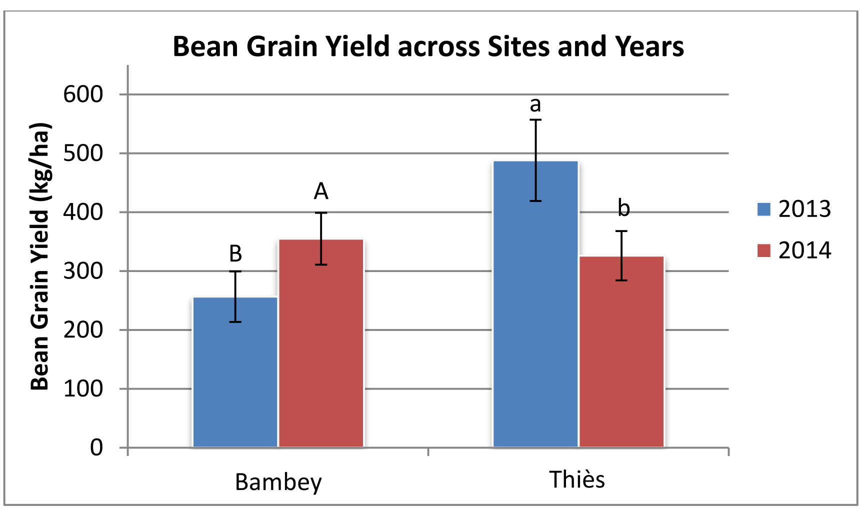


Figure 8. Average bean grain yields at Bambey and Thiès in 2013 and 2014. Treatments with the same letter are not significantly different from each other at alpha=0.05 (Fisher's LSD) and error bars were constructed using 1 standard error from the mean.

Although intercropping increased millet yields, the opposite effect was observed for bean yields (Figure 9). This reduction in bean yield in intercropping may be attributed in part to the competition for sunlight and nutrients between the two crops, as well as the lower plant populations of beans compared to the monocropped systems. As hypothesized, yields of the intercropped beans were <50% than that of the same beans grown in monocropping systems.

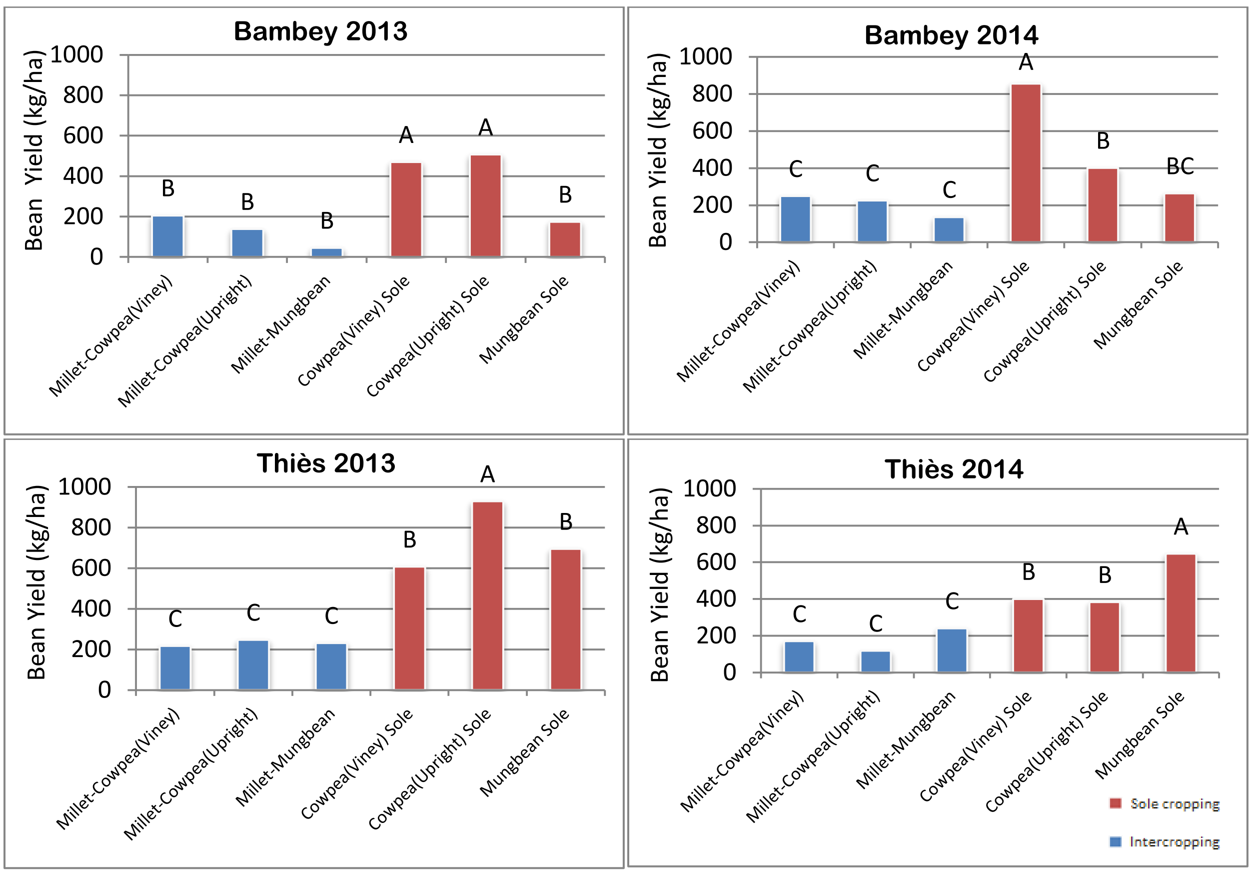


Figure 9. Average bean yields between monocropping and intercropping treatments at Bambey and Thiès in 2013 and 2014. Treatments with the same letter are not significantly different from each other at alpha=0.05 (Fisher's LSD).

Intercropping millet and beans together always yielded more grain than growing either the millet or the beans on their own. Every time millet was intercropped with the viney cowpea variety, the upright cowpea variety, or mungbean, there was higher overall grain production than could have been achieved had that plot been used to grow only sole millet or sole beans. In Bambey the three different intercropping treatments were distinctly advantageous compared to the monocropped treatments (not including the millet grown with mulch) (Figure 10).

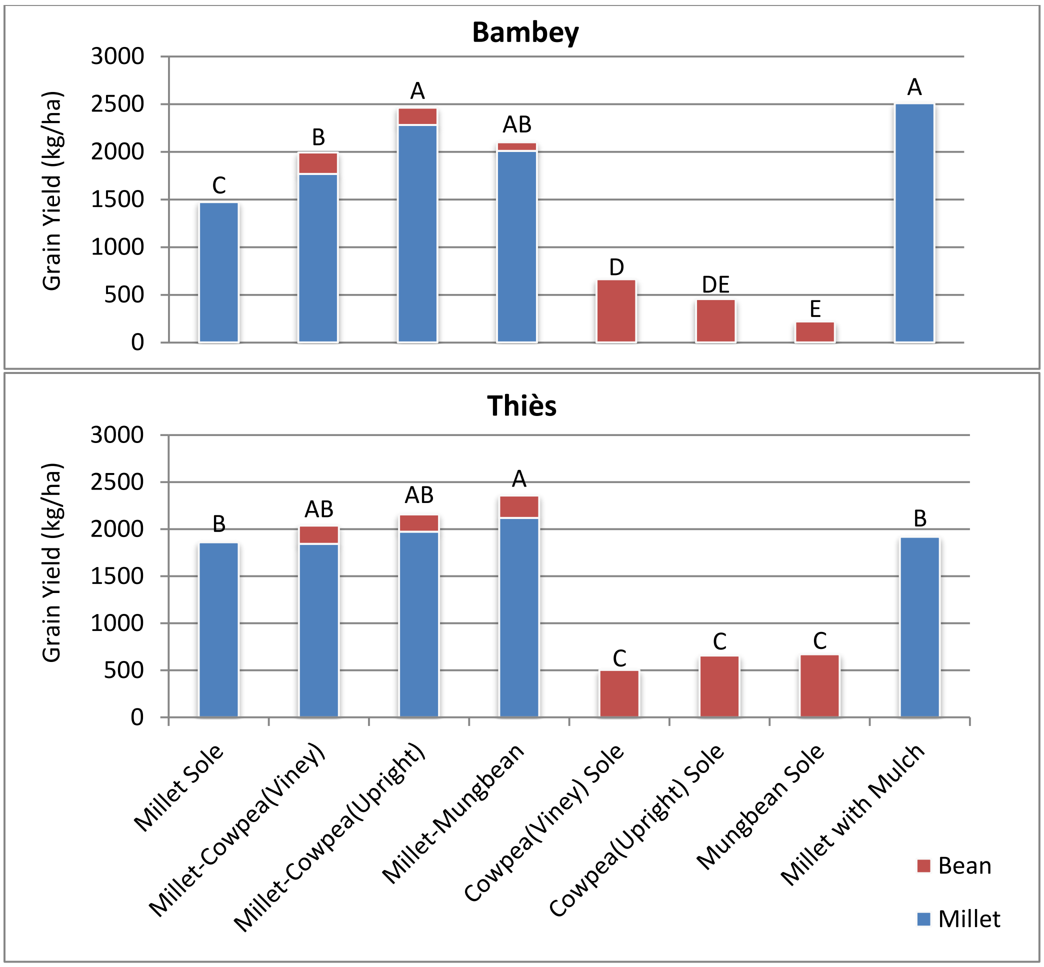


Figure 10. Combined grain yields between treatments at the Bambey site – yields are averaged over the 2013 and 2014 growing seasons. Treatments with the same letter are not significantly different from each other at alpha=0.05 (Fisher's LSD).

In Bambey, the millet-cowpea (upright) intercropping produced more combined grain than the other intercropping treatments, with total grain production of 2461 kg/ha. The yield advantage of the millet-cowpea (upright) treatment was 67% compared to millet in monoculture, and the millet-mungbean treatment yielded 43% more than millet grown alone. The lowest combined yield of the three intercropping treatments was the millet intercropped with the viney cowpea variety, which yielded 35% more than millet grown on its own. Even after combining the millet and bean grain together, the millet grown on the mulch was still the most productive system in Bambey. The millet grown with mulch produced 2510 kg/ha, a 70% increase over the millet grown alone.

The effect of intercropping on the combined yield was evident at both locations; however, the combination of treatments that resulted in the highest yields differed from Bambey to Thiès (Figure 10). At the Bambey location, the combined yield of the millet and the upright cowpea was higher than the millet grown alone and the millet grown with the viney cowpea. At the Thiès location, the combined yield of millet and mungbean was higher than the monoculture millet and the mulch treatments.

In addition to yield, number of panicles and average panicle length were measured at harvest (Table 7). In Bambey in 2014, where higher yields were observed in intercropping and mulched treatments, there were also higher numbers of panicles harvested from those same treatments. When panicle counts did not differ significantly between treatments, there too was little significant difference between yields of the same treatments. Differences in average panicle lengths changed very little between the different treatments. In the second year of the study, at both Bambey and Thiès, the mulched treatments had the highest average number of panicles.

			2013		2014	
Site	Trmt	Cropping System	Average Number of Panicles	Average Panicle Length (cm)	Average Number of Panicles	Average Panicle Length (cm)
Bambey (ISFAR)	1	Millet Sole	52 a	40 a	44 a	39 a
	2	Cowpea (Viney) Intercrop	62 a	37 c	49 bc	38 a
	3	Cowpea (Upright) Intercrop	64 a	38 bc	58 ab	38 a
	4	Mungbean Intercrop	56 a	39 b	55 b	39 a
	8	Millet with Mulch	68 a	39 ab	67 c	37 a
Thiès (ENSA)	1	Millet Sole	50 a	38 b	57 b	36 ab
	2	Cowpea (Viney) Intercrop	41 a	39 ab	58 ab	38 ab
	3	Cowpea (Upright) Intercrop	52 a	40 a	52 b	39 a
	4	Mungbean Intercrop	51 a	39 ab	63 ab	37 ab
	8	Millet with Mulch	46 a	38 b	69 a	37 b

*Treatments not connected by the same letter are significantly different (Fisher's LSD)

Table 7. Summary of additional millet yield components at Bambey and Thiès for the 2013 and 2014 growing seasons. Treatments with the same letter are not significantly different from each other at alpha=0.05 (Fisher's LSD).

Soil Moisture

Daily soil moisture data taken throughout the growing season indicate that intercropping treatments did not retain more soil moisture that the monocropping treatments on average. Despite the increased ground cover provided by the cowpea and the mungbean, there was no increase in Volumetric Water Content (VWC). However, the difference in soil moisture contents between the millet grown with the mulch and the traditional monoculture treatments (no ground cover) was significant. In Bambey, during the 2014 growing season, the soil under the mulched treatment had an average of 11.12% VWC throughout season, compared to 9.73% VWC for millet grown without any ground cover (Figure 11). This represents a 14% increase in soil moisture over the traditional monoculture millet practices.

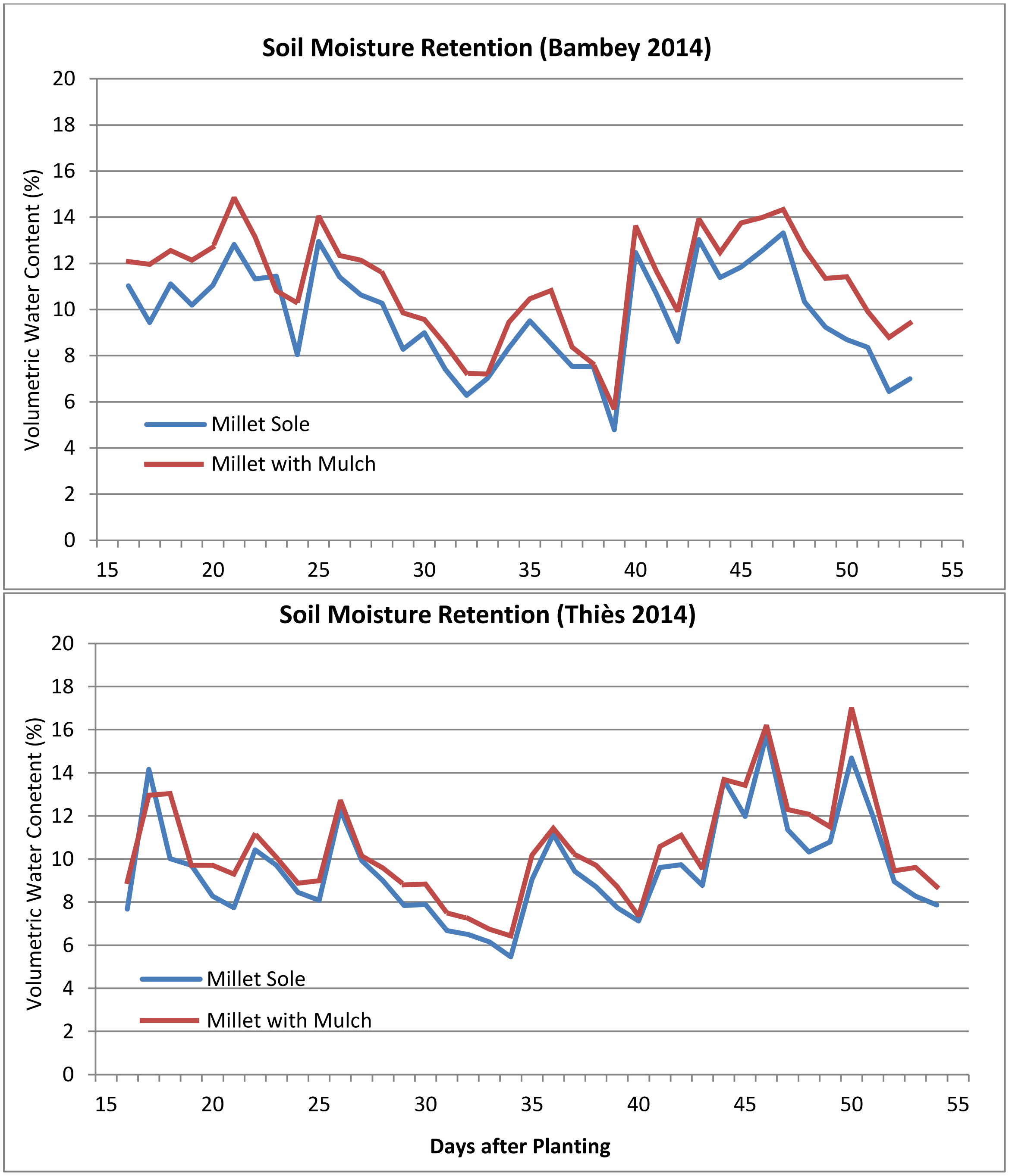


Figure 11. Daily soil volumetric water content (VWC) data collected at Bambey and Thiès during the 2014 growing season.

A similar trend was recorded in Thiès, where the mulched soils consistently retained more moisture than non-mulched soils (Figure 11). During the 2014 growing season at Thiès, the mulched treatment recorded an average VWC of 10.43% while the millet grown alone recorded an average of 9.56%. This translates to an average increase in soil VWC of 9% during the days recorded, less than was observed at Bambey.

Normalized Difference Vegetation Index (NDVI)

The Normalized Difference Vegetation Index (NDVI) growth curves follow the same basic trends as that of the yield data; with millet grown by itself showing the weakest curve, followed by the three intercropping treatments in the middle, and the millet grown with a mulch yielding the greatest curve. In every case, across both years and at both sites, the NDVI curves of millet intercropping treatments and millet treatments grown with mulch were always greater than those of treatments where millet was grown on its own (Figure 12).

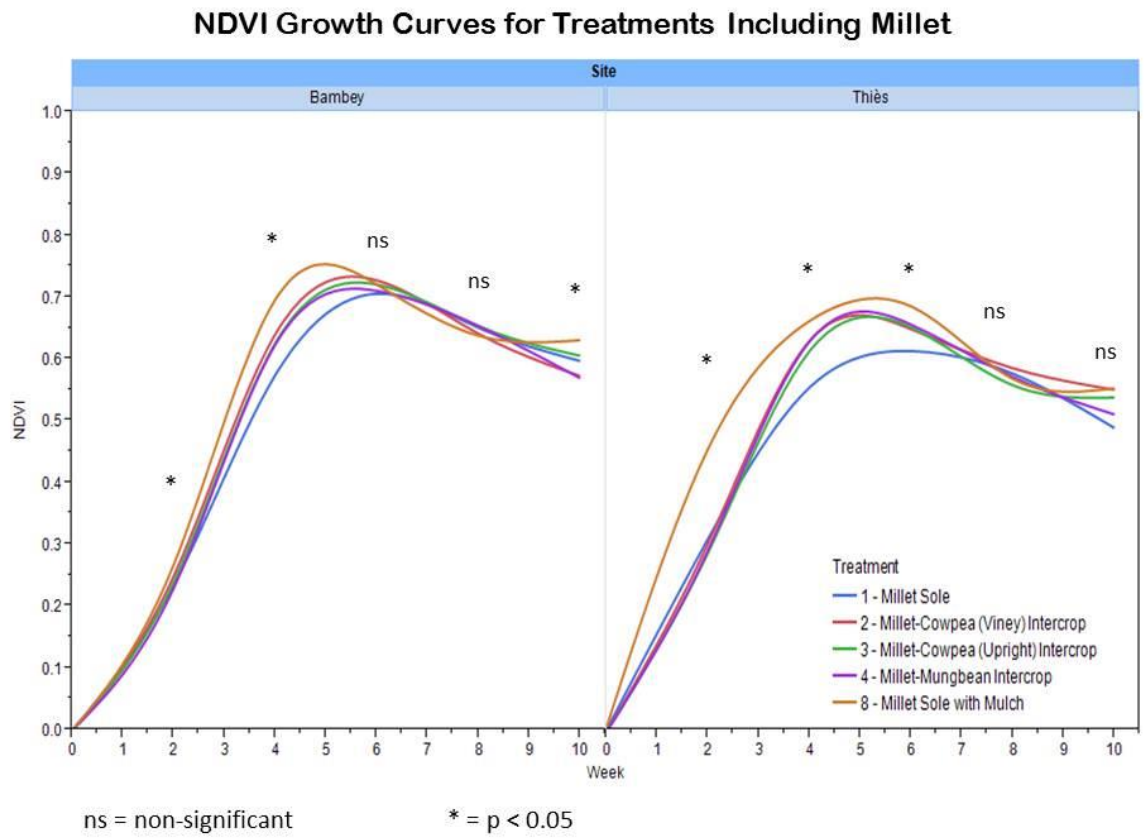


Figure 12. Millet NDVI growth curves at Bambey and Thies, averaged across 2013 and 2014.

Discussion

Our experiment showed that millet yields increased when grown in association with cowpea and mungbean. A similar study conducted in Niger by Reddy *et al.* also reported increased millet yields when millet was intercropped with cowpea (Reddy *et al.*, 1992). Reddy and his colleagues reported 14-15% yield increase when millet was intercropped with cowpea compared to millet grown alone. However, other researchers have reported decreases in millet yield when grown in association with legumes. One such report, conducted by Grema and Hess (1994) documented 34% and 23% yield reduction when millet was grown in association with two different cowpea varieties (local and improved) (Grema and Hess, 1994). A study conducted in Senegal also showed lower millet yields grown in association with legumes, compared to when grown alone (Diangar *et al.*, 2004). The percentage yield declines they reported were 16-24% depending on the region (16% central-north vs 24% central-south) (Diangar *et al.*, 2004).

Unlike the intercropped millet, where millet yield was increased, the opposite effect was observed for bean yields. Reddy *et al.* (1992) reported similar results where bean yields were reduced significantly when grown with millet as compared to when they were grown on their own. Similar to our results, the yield reductions they reported for intercropped beans were 36% and 48% for year 1 and 2, respectively. Overall, despite no outstanding differences in yield among the beans varieties, there is evidence to suggest that the viney cowpea variety appears to have had higher yields compared to the upright varieties of cowpea and mungbean.

All three of the intercropping treatments were highly productive compared to each of the monocropping treatments. The millet-cowpea (upright) intercropping system yielded the highest, with a Land Equivalency Ratio of 2.00 (Appendix Figure B5). The millet-mungbean intercropping system had the next highest value with an LER of 1.87, followed by the millet-cowpea (viney) variety which had an LER of 1.68. The overall LER values for the intercropping treatments in Thiès were lower than that of Bambey, but were still all considerably higher than one (Appendix Figure B5). There was not much distinction between the three different treatments, as they all experienced similar LER values. The millet-mungbean intercropping system yielded the highest LER, with a value of 1.52, while the millet-cowpea (viney) and the millet-cowpea (upright) systems had LER values of 1.47 and 1.42, respectively.

In their study conducted in Niger, Reddy *et al.* (1992) recorded LER values for different millet-cowpea intercropping systems that had cowpea planted into the millet stand at increasing intervals. LER values of 1.48, 1.43, and 1.08 were recorded for systems where cowpea was planted one, two, and eight weeks after millet planting respectively. Although experiments were conducted at different sites with different varieties, a comparison of LER values would suggest that simultaneous planting of cowpea and millet is more beneficial overall.

The yield compatibility of the newly introduced mungbean crop, varied considerably across years and sites. While the mungbean yield was relatively competitive with cowpea at the Thiès location, the yields were extremely low at the Bambey location. However, when mungbean was at its best, it did out-produce the strongest cowpea stands, in terms of grain production. To our knowledge, intercropping mungbean with millet in Senegal has not been studied; therefore there are no existing results to compare with.

As reported previously, the most dramatic yield increases of all of the treatments was observed in the treatments where millet was grown with a mulch (up to 70% yield increase in Bambey). The increased millet yield associated with the mulch treatment can be attributed in part to a much better soil moisture status for the mulched treatments compared to the intercropping and traditional monoculture millet treatments (Figure 11). In addition to improving soil moisture status, residues on the soil surface can reduce the splash-effect of raindrops resulting in higher infiltration and reduce runoff, leading to less erosion (FAO, 2015). This result highlights the value of maintaining ground cover on soils that are highly susceptible to excessive water loss like soils found in most millet growing regions in Senegal.

Rebafka *et al.* (1994) found similar results in Niger using crop residues as mulch in millet fields. In their study, in which they compared the effects of short-term and long-term application of mulches, they found that the application of crop residues increased dry matter yields more than 60% in pearl millet, while the omission of the crop residues decreased yields (Rebafka *et al.*, 1994). To examine the effect of mulch on soil moisture status, Buerkert *et al.* (2000) conducted an experiment involving the addition of 2000 kg/ha of mulch across three of West Africa's primary climatic zones (Sahel, Sudanian, and Guinean). They reported beneficial effects of mulch on soil moisture content, more specifically in in the Sahel regions (Buerkert *et al.*, 2000). Furthermore, Buerkert, *et al.* (2000) found consistent increases in soil moisture levels in the 0-30cm range over plots that were not treated with mulch. Mulumba and Lal (2008) analyzed soils under long-term (11 years) mulch in Ohio and found an increase in available water capacity by 18-35% in the upper 10cm of the soil. While they used high rates of mulch (8 t/ha and 16t/ha) in the experiment, they concluded that 2 t/ha of mulch (the same amount applied in our study) was enough to achieve 75% of these moisture retention rates (Mulumba and Lal, 2008).

Our experiment implemented conservation agriculture principles which included the maintenance of ground cover, minimum tillage, and crop diversification. Among the long list of potential benefits of conservation agriculture are soil moisture conservation, erosion control, improved soil health, and a diversified cropping system. Our two year experiment showed a promising potential to improve yields through conservation agriculture practices such as the inclusion of leguminous crops, ground cover establishment, and diversified cropping systems. In a country like Senegal, which is heavily dependent on agriculture, conservation agriculture can offer potential for improving rural livelihoods and breaking the downward spiral of poverty, soil degradation, and declining productivity.

Summary and Conclusions

The three different intercropping systems evaluated in this study each produced more grain per unit of land area than any of the monocropped millet or beans. The primary cereal crop millet generally experienced increases in grain yields when intercropped with any of the three bean varieties. Although the addition of beans increased the total grain yield, the effect of intercropping on bean yield was negative. The lack of response in bean yield grown in association with millet compared to the beans grown alone can be partially explained by shading of beans by the millet plant, as well competition between crops for limited resources.

Our experiment clearly showed that the addition of each bean crop, regardless of morphological characteristic or type, greatly improved millet production and overall grain production. However, the percentage increases in millet yields, due to the addition of beans in the system, greatly varied by bean type and location. There is evidence to suggest that intercropping an upright bean variety (cowpea or mungbean) may have the potential to produce higher yields overall than intercropping a viney or spreading variety. At both sites, the cropping systems that included upright bean varieties did produce higher overall yields.

Growing millet on mulch also proved to have beneficial effects on millet yields. In every case that millet was grown under a layer of well-established mulch (neem leaves), there was an increase in millet grain yield over that of millet grown alone without ground cover. In this study the mulched plots resulted in 17-70% millet yield increases over the untreated control. The positive effect of the use of mulch on the millet yield can be explained in part by the enhanced water conservation.

Table 8 shows the summary of previous millet-cowpea intercropping studies and results in West Africa in comparison to results obtained in our experiment. Our experiment clearly showed the benefits of intercropping on overall yields and higher Land Equivalency Ratios. Although no replicated measurements were taken to confirm the effect of the rhizobacteria on cowpea and mungbean nodulation in Senegal's growing conditions, we can speculate that the inoculation of the cowpea and mungbean may have been a driving factor in the yield increases observed in our study. To observe the effectiveness of the inoculum on the cowpea and mungbean, a small non-replicated trial compared nodulation between inoculated and non-inoculated beans. Considerable increases in root nodulation in the inoculated cowpea and mungbean were observed (Appendix Figure B4). Further replicated research would be necessary to confirm our observations.

Site	Millet Sole (kg/ha)	Millet Intercrop (kg/ha)	Experimental Details	LER	Source
Niger	580	710 ↑	(1 WAMP)*	1.48	(Reddy et al., 1992)
		780 ↑	(2 WAMP)*	1.43	
		580 ↓	(8 WAMP)*	1.08	
Nigeria	1390	920 ↓	(Local cowpea variety)	-	(Grema and Hess, 1994)
		1070 ↓	(Improved cowpea variety)		
Niger	1380	1060 ↓	(Early Erect Cowpea)	-	(Ntare, 1990)
		1040 ↓	(Early Spreading Cowpea)		
		340 ↓	(Late Spreading Cowpea)		
Senegal	1456	1220 ↓	(Central North)	1.06**	(Diangar et al., 2004)
	1534	1170 ↓	(Central South)	1.37**	
Senegal	1667	2127 ↑	(Upright Cowpea)	1.42-2.00	(Trail, 2014)
		1805 ↑	(Viney Cowpea)	1.47-1.68	
		2064 ↑	(Mungbean)	1.52-1.87	

* WAMP – Weeks After Millet Planting
** The highest values were chosen from the multiple millet and cowpea variety combinations tested
↑ Increase over sole millet yields
↓ Decrease over sole millet yields

Table 8. Results of similar millet-cowpea intercropping studies conducted across West Africa

Growing millet on mulch showed beneficial effects on millet yields. The yearly addition of leaf organic matter into the soil may eventually build soil organic matter, which may potentially lead to enhanced CEC, soil water holding capacities, and improved soil aggregation.

The broader application of these results demonstrate that grain yields can be increased with the adoption of these conservation agriculture practices, and can be done so without the application of external inputs that may or may not be available to many farmers in Senegal. These results demonstrated that there are multiple potential advantages of adapting these practices to the smallholder farmers of Senegal, which include:

- Growing and harvesting two different crops on the same piece of land within the same growing season.
- Overyielding – which occurs (in this case occurred), when the combined yield produced in intercropping is larger than the yield produced by either of the individual crops grown in monoculture.
- The use of crops with different growth habits and stages of maturity (planting to harvest) within the cropping system. Early season grain legumes like mungbean (45-50 days from planting to harvest), or short season cowpea are often the first available food crop at the end of a long hunger season. Mungbean utilized in this experiment (as well as several farmers' fields in Senegal) showed a great deal of potential in providing a much needed grain crop earlier in the growing season.
- The added benefit of growing a protein crop like cowpea or mungbean with the primary cereal crop (in this case millet) can improve the nutritional quality of the local diets.

- By growing two different crops in the same season, a farmer can minimize the risks of individual crop failure (due to drought or pest damage) by growing crops that have different tolerances to different environmental factors.
- The addition of leguminous crops with the ability to biologically fix nitrogen and can add N back into the system.

References

Bationo, A. and B.R. Ntare. 2000. Rotation and nitrogen fertilizer effects on pearl millet, cowpea and groundnut yield and soil chemical properties in a sandy soil in the semi-arid tropics, West Africa. The Journal of Agricultural Science 134: 277-284.

Buerkert, A., A. Bationo and K. Dossa. 2000. Mechanisms of Residue Mulch-Induced Cereal Growth Increases in West Africa11 Dedicated to Horst Marschner and his commitment to process-oriented soil fertility research in West Africa. Soil Sci. Soc. Am. J. 64: 346-358.

Buerkert, A. and J. Lamers. 1999. Soil erosion and deposition effects on surface characteristics and pearl millet growth in the West African Sahel. Plant Soil: 239-253.

Diangar, S., A. Fofana, M. Diagne, C.F. Yamoah and R.P. Dick. 2004. Pearl millet-based intercropping systems in the semiarid areas of Senegal. African Crop Science Journal 12: 133-139.

FAO. 2015. What is Conservation Agriculture? United Nations Food and Agriculture Organization - Agriculture and Consumer Protection Department. http://www.fao.org/ag/ca/1a.html (accessed 10 Feb. 2015.)

FAOSTAT. 2013. Average millet yields in Senegal compared to West Africa and India. United Nations Food and Agriculture Organization - Division of Statistics. http://faostat3.fao.org/download/Q/QC/E (accessed 10 Feb. 2015.)

Fofana, B., M.C.S. Wopereis, A. Bationo, H. Breman and A. Mando. 2008. Millet nutrient use efficiency as affected by natural soil fertility, mineral fertilizer use and rainfall in the West African Sahel. Nutrient Cycling in Agroecosystems 81: 25-36.

Fussell, L.K., M.C. Klaij, C. Renard and B. N'Tare. 1989. Millet based production systems for improving food production in the southern Sahelian zone. Farming Systems Research Workshop on Appropriate Technologies for Achieving Sustainable Food Production Systems in Semi-Arid Africa. Ouagadougou, Burkina Faso.

Grema, A.K. and T.M. Hess. 1994. Water balance and water use of pearl millet-cowpea intercrops in north east Nigeria. Agric. Water Manage. 26: 169-185.

Lahmar, R., B.A. Bationo, N.D. Lamso, Y. Guéro and P. Tittonell. 2012. Tailoring conservation agriculture technologies to West Africa semi-arid zones: building on traditional local practices for soil restoration. Field Crops Res. 132: 158-167.

Mulumba, L.N. and R. Lal. 2008. Mulching effects on selected soil physical properties. Soil and Tillage Research 98: 106-111.

Ntare, B.R. 1990. Intercropping Morphologically Different Cowpeas With Pearl Millet in a Short Season Environment in the Sahel. Exp. Agric. 26: 41-47.

Rebafka, F.P., A. Hebel, A. Bationo, K. Stahr and H. Marschner. 1994. Short- and long-term effects of crop residues and of phosphorus fertilization on pearl millet yield on an acid sandy soil in Niger, West Africa. Field Crops Res. 36: 113-124.

Reddy, K.C., P. Visser and P. Buckner. 1992. Pearl millet and cowpea yields in sole and intercrop systems, and their after-effects on soil and crop productivity. Field Crops Res. 28: 315-326.

Stoskopf, N.C. 1985. Pearl Millet. Cereal Grain Crops. Reston Publishing Company, Inc., Reston, Virginia. p. 429-444.

The Climate Research Unit of East Anglia. 2014. Average monthly temperature and rainfall for Senegal at location (14.72,-16.61) from 1990-2009. The World Bank Group, Climate Change Knowledge Portal. http://sdwebx.worldbank.org/climateportal/index.cfm?page=country_historical_climate&ThisRegion=Africa&ThisCCode=SEN (accessed 17 Nov. 2014.)

Tilander, Y. and M. Bonzi. 1997. Water and nutrient conservation through the use of agroforestry mulches, and sorghum yield response. Plant Soil 197: 219-232.

Chapter IV: Summary and Conclusions

Many of the treatments evaluated in this study proved to be beneficial in terms of increasing grain production, and show great potential as agronomic tools for small-scale subsistence farmers in this region of Senegal. In addition to improving yields, these specific practices also adhere in many ways to traditional agronomic practices and don't require drastic changes from farmers' current practices. In the intercropping systems, millet planting densities were left unchanged while a row of beans was simply added between rows. Weeding, which is typically performed with a draft-powered cultivator, would remain the same since the new intercropping row widths are identical to that of peanut row widths. Typical peanut row widths in the millet-peanut basin are 50 cm wide, the same row spacing between millet and beans in this study.

These intercropping and mulching practices also incorporate well the core concepts of Conservation Agriculture (CA) and can easily be adapted to include the three foundational practices of (1) minimum tillage (2) year-round soil cover, and (3) crop diversification. By minimizing tillage and leaving the previous year's crop residues in the field, intercropping is distinctly suited to serve as a CA practice. Mulching practices can be used specifically as year-round soil cover in many different cropping situations to ensure that all three of the CA core principles are well monitored.

In terms of adaptation of CA practices by local farmers, several of the principles can be easily incorporated with the current (farmer's) practices. For example, intercropping alone can help minimize soil disturbance and can potentially produce crop residues. The effectiveness of mulching on both yield increases and moisture conservation was clearly demonstrated in our experiment. Where farmers prefer growing millet in monoculture as opposed to intercropping, mulching can instead be used to effectively address some of the principles of conservation agriculture. If mulching materials are available year round, then crop residues can still be used for their traditional functions (livestock feed, building material, etc…) and would not need to be split between dual roles. During the dry season (November - July), animals alone can easily remove 100% of the crop residue leaving the soil surface totally bare, making mulching practices that much more necessary.

In 2012, Virginia Tech, in collaboration with USAID-ERA and several partner institutions in Senegal introduced the mungbean crop as alternative food legume. Within a year, the legume gained a tremendous amount of popularity among farmers and seed producers. Some of this crop's beneficial attributes include a quick and aggressive start, short season or early maturing (40-50 days from planting to harvest), and a crop residue that breaks down relatively quickly. In our experiment, the inclusion of mungbean not only increased millet yield when intercropped with millet but also produced competitive yields to that of cowpea when grown alone. More research will be needed to further explore the wide adaptation of mungbean throughout Senegal.

Finally, it is important to note that these field experiments were implemented without the use of fertilizers in an attempt to demonstrate that there are yield gains to be had, even for the smallholder farmer who may not necessarily have the means to purchase them. This research is by no means suggesting that fertilizers should not be applied, but rather is aimed at helping the farmer that may not have the luxury of obtaining fertilizers.

Appendices

Appendix A – Supplemental Data

Table A. Soil analysis summary for the Bambey and Thiès field sites in 2013 – anlaysis was completed by faculty at the École Nationale Supérieur d'Agriculture (ENSA) in Thiès

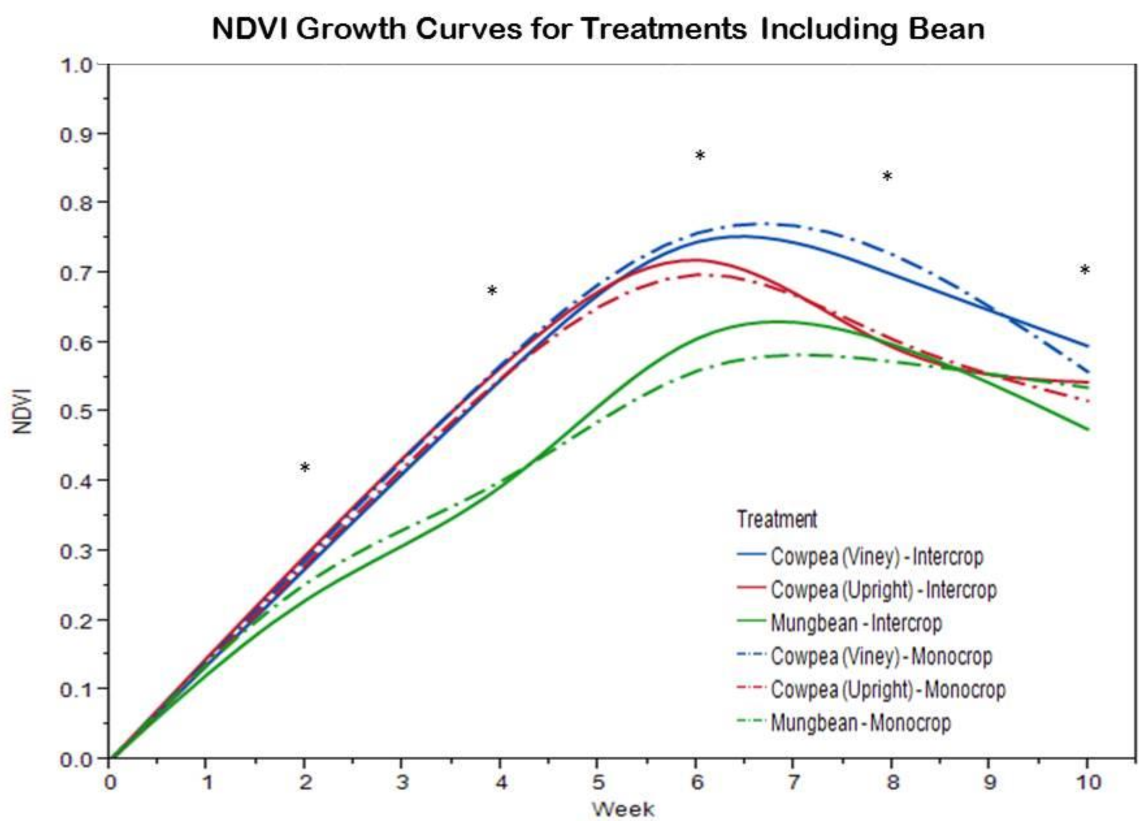
ANALYSES ECHANTILLON	PH 1 :2.5	Conduct Elec uS à 20 degrés	CARBONE %	AZOTE %	CEC Meq/100g	GRANULOMETRIE %			
						A	LF	LG	S
1). THIES 4/1/13	7, 37	127,6	0,61	0.06	7	6.5	3.25	3.5	86.75
2). THIES 4/1/13	7, 48	116	0,18	0.06	6	10	3.25	2.25	84.5
3). THIES 3/4/13	7, 50	133,4	0,06	0.06	7	6.5	5	1	87.5
4). BAMBEY 05/3/13	6, 22	88,2	0,61	0/19	4	6.5	5.25	2.25	86
5). BAMBEY 01/3/13	6, 66	106,7	0,18	0.09	6	6	2.25	5.25	86.5
6). BAMBEY 05/3/13	7, 20	197,2	0,98	0.13	6	4.25	8.25	13	74.5

Table B. Summary of bean pod counts at Bambey and Thiès in 2013 and 2014

		2013		2014	
Site	Crop Variety	Average Number of Pods per Plant		Average Number of Pods per Plant	
		Sole Crop	Intercrop with Millet	Sole Crop	Intercrop with Millet
Bambey (ISFAR)	Cowpea (Viney)	12	10	26	13
	Cowpea (Upright)	13	8	10	9
	Mungbean	16	8	20	13
Thiès (ENSA)	Cowpea (Viney)	14	10	9	6
	Cowpea (Upright)	11	6	7	4
	Mungbean	33	22	31	20

Figure C. Bean NDVI growth curves from planting to harvest – values are averaged over both sites and both years.

According to NDVI data logged on the different bean crops, there was a clear trend between the three different bean treatments. Whether grown alone, or intercropped with millet, it was always the cowpea viney variety that recorded the greatest NDVI curve, followed by the cowpea upright variety and then the mungbean. Since trends were the same in each case, NDVI curves for the three bean crops were averaged over the two sites and the two years and presented in Figure 14. There were no consistent differences between beans that were monocropped compared to beans that were intercropped.



ns = non-significant   * = p < 0.05

Looking at these NDVI curves, it is interesting to note that the intercropping bean treatment that performed the best on its own (the cowpea viney variety) was also the treatment that recorded the lowest average millet yields when grown in association. Conversely, it was the millet grown with the upright bean varieties (cowpea and mungbean) that appear to have performed more poorly when intercropped, but produced the higher millet yields.

Similar results were recorded in the study conducted in Niger by Ntare (1990) when morphologically different cowpea varieties were intercropped with millet. In his study Ntare found that while the spreading cowpea variety performed better than the erect variety when intercropped with millet, it was the millet intercropped with the spreading variety that yielded the least. The erect cowpea variety in his study yielded 0.35 t/ha when intercropped with millet, while the spreading variety yielded 0.49 t/ha. At the same time, the millet intercropped with the erect cowpea yielded 1.06 t/ha, slightly better than the millet intercropped with the spreading variety. Our study found greater differences in millet yield when millet was intercropped with two morphologically different varieties. Ntare's study recorded decreases in intercropped millet yields when compared to millet grown on its own. Intercropped millet grain yields in his experiment decreased 23% on average when intercropped with cowpea, which was the opposite trend of what was recorded in our study in Senegal.

Figure D. The effect of rhizobacteria inoculation on the rate of nodulation for the different bean crops – a small side study was conducted in Thiès in 2014

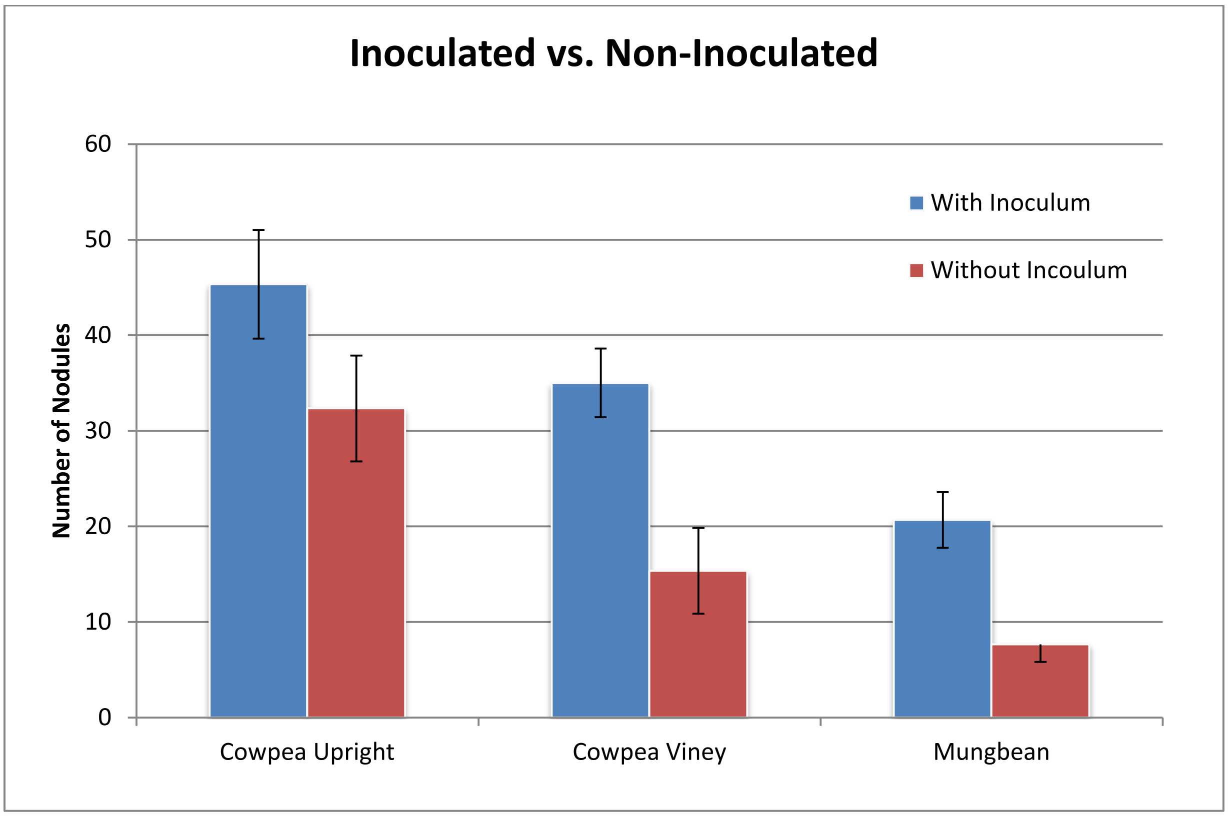
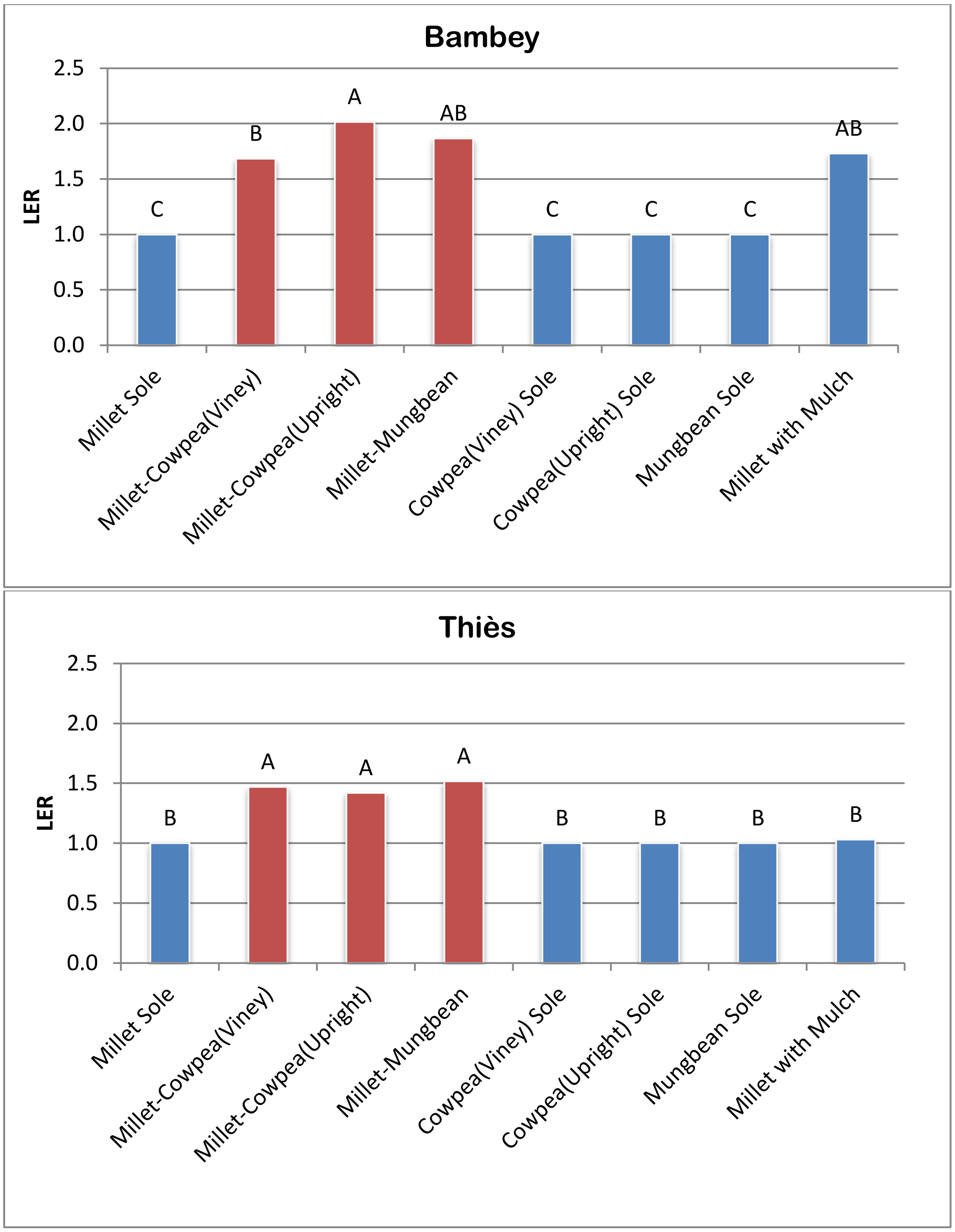


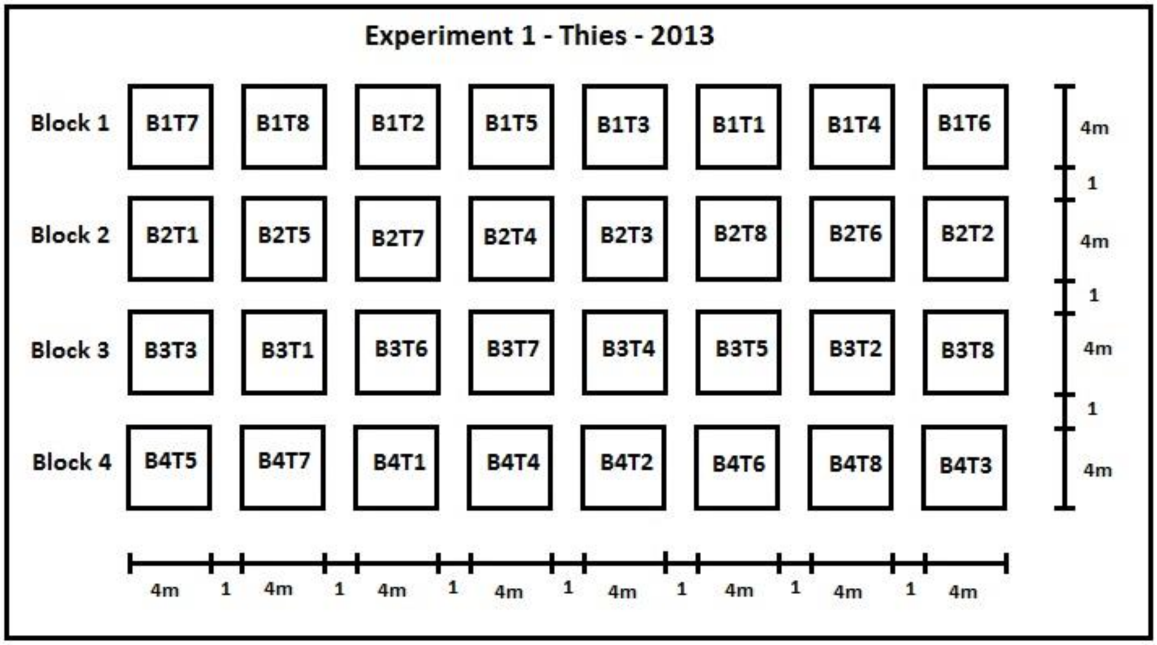
Figure E. Land Equivalency Ratios between monocropping and intercropping systems in Bambey and Thiès– average LER values over the 2013 and 2014 seasons



Appendix B – Experimental Design

Figure F. Site map of university research stations and on-farm field trials

Figure G. Diagram of the plot layout including all eight treatments (Randomized Complete Block Design)



Appendix C – Reference Material

Figure H. Varietal factsheet for millet – ISMI 9507 – provided by the Institut Sénégalais de Recherches Agricoles (ISRA)

Identification	
Nature génétique : synthétique ISRA	**Année d'obtention :** 1995
Vocation culturale : hivernage et contre saison	
Origine : ISRA/Bambey	**Zone de recommandation :** Centre Nord du BA
Caractères de la plante	
Cycle semis - floraison : 60	**Hauteur de la plante (cm):** 220
Cycle semis - récolte : 85	**Longueur de l'épi (cm):** 45
Compacité de l'épi : Bonne	**Tallage (épis/poquet) :** Bon (4 à 6)
Rendement au battage (%) : 65	**Forme de l'épi :** Cylindrique
Exsertion (séparation épi avec la feuille paniculaire) : Bonne	
Caractéristiques agronomiques et sensibilité par rapport aux maladies	
Rendement en grains (station Bambey)	**Mildiou :** Faible
Rendement maximum (t/ha): 3,0	**Charbon :** Très faible
Rendement moyen (t/ha): 2,4	**Ergot :** Très faible
Fertilisation : NPK (15-15-15/15-10-10) 150kg/ha	**Semences :** 4kg/ha
Urée : (46-0-0, 2 tranches de 50kg/ha chacune	**Disque :** 4 trous ou 90cm X 90cm
Tests physicochimiques	
Teneur en protéine	**Taux de glucide**
Taux de cendre	**Vitrosité**
Teneur en phosphore	
Tests d'aptitudes technologiques	
Rendement au décorticage	**Aptitude au roulage**
Rendement à la mouture	**Aptitude à la panification**
Tests d'aptitudes culinaires	
Acceptabilité du couscous : Bonne	**Acceptabilité du fondé :** Bonne

Figure I. Varietal factsheet for viney cowpea variety – Mélakh – Provided by the Institut Sénégalais de Recherches Agricoles (ISRA)

VARIÉTÉ DE NIÉBÉ

Mélakh

DESCRIPTION GENERALE

Date d'obtention : **1989**
Date d'homologation :
Espèce : ***Vigna unguiculata* (L.) Walp.**
Synonyme : ***Vigna sinensis* (L.) Savi**
Pedigree : **IS86-292 x IT83s-742-13**
Nature génétique : **Lignée pure**
Obtenteur : **ISRA**
Lieu de sélection : **Bambey, Sénégal**
N° de sélection : **B 89-504**

CARACTERISTIQUES D'IDENTIFICATION

Caractéristiques de la plante

Pigmentation anthocyanique de la plante : **Absente**
Port : **Semi-rampant**
Croissance : **Indéterminé**
Hauteur de la tige principale (soutenue) :
Couleur des feuilles : **Vert foncé**
Cycle 50% floraison : **34 jas**[*]
Couleur de la fleur : **Blanche**
Gousse *(à maturité pour le marché du frais)* :

- Longueur : **20 cm**
- Largeur : **2 cm**
- Torsion : **Absente**
- Pigmentation anthocyanique : **Absente**
- Nombre de gousse par pédoncule :
- Couleur : **Verte**
- Forme : **Longue**

Caractéristiques de la graine

Poids de 100 graines : **17,5 gr.**
Longueur : **8,0 mm**
Forme : **Réniforme**
Couleur principale : **Blanc crème**
Présence de couleur secondaire : **Présente**
Distribution de la couleur secondaire : **Hile**

CARACTERISTIQUES AGRONOMIQUES et TECHNOLOGIQUES

Vocation culturale : **Culture irriguée ; pluviale (Fleuve Sénégal, Louga, Diourbel, Dépt. de Tivaouane)**
Cycle 95% maturité : **52 – 61 jas**
Cowpea (yellow) mosaic virus (CPMV) : **Présente**
Résistance au chancre bactérien : **Absente**
Résistance au striga : **Absente**
Résistance à *Amsacta* : **Absente**
Résistance aux pucerons : **Présente**
Résistance aux thrips : **Absente**
Résistance aux bruches : **Absente**
Rendement graines : **1,0 t/ha**
Rendement battage :
Rendement en fanes :

Figure J. Varietal factsheet for upright cowpea variety – Yacine – Provided by the Institut Sénégalais de Recherches Agricoles (ISRA)

VARIETE DE NIEBE

Yacine

DESCRIPTION GENERALE

Date d'obtention : **1991**
Date d'homologation : **18 février 2010**
Espèce : ***Vigna unguiculata* (L.) Walp.**
Synonyme : ***Vigna sinensis* (L.) Savi**
Pedigree : **Mame Penda x Mélakh**
Nature génétique : **Lignée pure**
Obtenteur : **ISRA**
Lieu de sélection : **Bambey, Sénégal**
N° de sélection : **ISRA 819**

CARACTERISTIQUES D'IDENTIFICATION

Caractéristiques de la plante

Pigmentation anthocyanique de la plante : **Absente**
Port : **Érigé**
Croissance : **Déterminé**
Hauteur de la tige principale (soutenue) :
Couleur des feuilles : **Vert foncé**
Cycle 50% floraison : **35 jas**
Couleur de la fleur : **Concolor blanche**
Gousse *(à maturité pour le marché du frais)* :

- Longueur : **18 cm**
- Largeur : **2,5 cm**
- Torsion : **Absente**
- Pigmentation anthocyanique : **Absente**
- Nombre de gousse par pédoncule :
- Couleur : **Verte**
- Forme : **Longue**

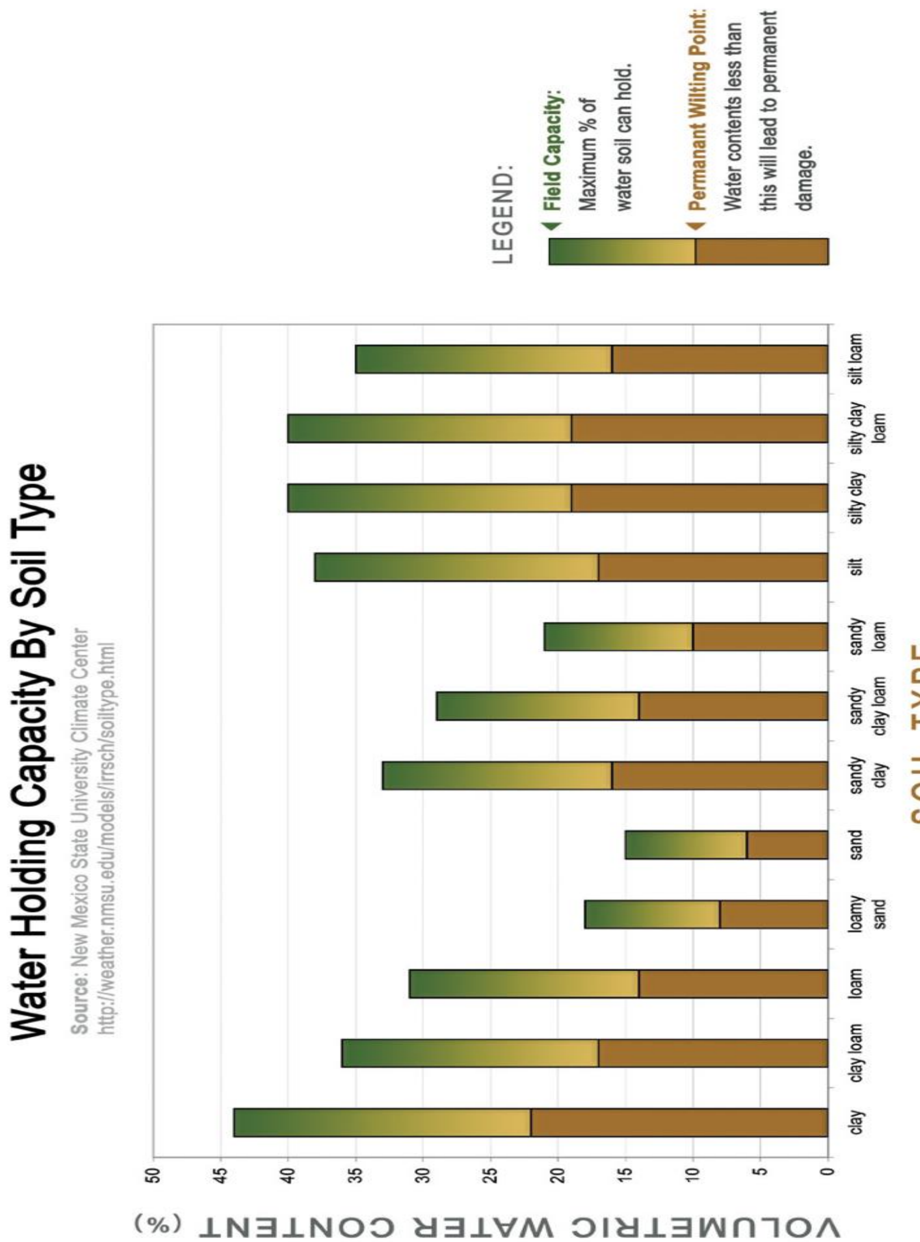
Caractéristiques de la graine

Poids de 100 graines : **25 gr.**
Longueur :
Forme : **Réniforme**
Couleur principale : **Marron**
Présence de couleur secondaire : **Absente**
Distribution de la couleur secondaire : **Aucune**

CARACTERISTIQUES AGRONOMIQUES et TECHNOLOGIQUES

Vocation culturale : **Cultures irriguée ; pluviale (Fleuve Sénégal, Louga, Thiès, Diourbel)**
Cycle 95% maturité : **62 jas***
Cowpea (yellow) mosaic virus (CPMV) : **Présente**
Résistance au chancre bactérien : **Présente**
Résistance au striga : **Absente**
Résistance à *Amsacta* : **Absente**
Résistance aux pucerons : **Présente**
Résistance aux thrips : **Absente**
Résistance aux bruches : **Absente**
Rendement graines : **2,5 t/ha**
Rendement battage :
Rendement en fanes :

Figure K. Water holding capacity (VWC) for different soil types (NMSU Climate center, 2014)



NMSU Climate Center. 2014. Water holding capacity by weather type. New Mexico State University Climate Center. http://weather.nmsu.edu/models/irrsch/soiltype.html (accessed 12 Feb. 2015.)

Figure L. Ground cover percentage calculation method – completed in ERDAS Imagine remote sensing software package.