Canadian Foodgrains Bank
A Christian Response to Hunger

SOIL HEALTH IMPACTS of Conservation Agriculture in Sub-Saharan Africa

AGRICULTURE & LIVELIHOODS GUIDANCE NOTE

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Canada

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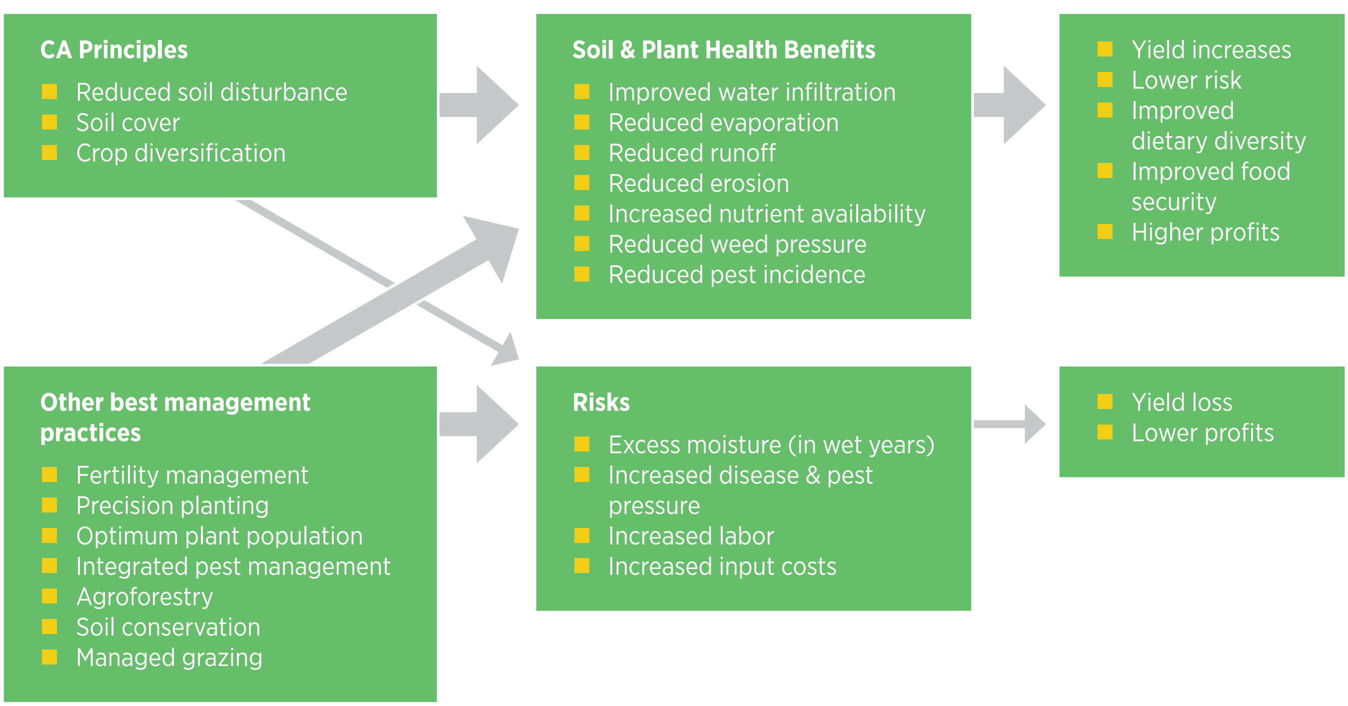
AGRICULTURE & LIVELIHOODS CAPACITY DEVELOPMENT PROGRAM

The agriculture community is increasingly recognizing soil health as deeply important to the function and productivity of agricultural systems. The Scaling up Conservation Agriculture (SUCA) program of the Canadian Foodgrains Bank was a five year program to promote conservation agriculture as a means to improve soil health, and increase crop yields, farm profitability, dietary diversity, and food security on smallholder farms in East Africa. This Guidance Note summarizes the impacts of conservation agriculture on various aspects of soil health for agricultural ecosystems in the tropics, and especially Sub-Saharan Africa. It draws on published scientific literature, farmer and staff experience, and a soil health survey conducted in Kenya, Ethiopia, and Tanzania as part of the SUCA program.

What is Conservation Agriculture?

Conservation agriculture (CA) is a set of practices intended to improve soil health and increase crop yields, especially on degraded soils. The three core CA principles, as defined by the Food and Agriculture Organization of the United Nations, are:

1. Minimum mechanical soil disturbance (i.e. no tillage) through direct seed and/or fertilizer placement. Minimum tillage can be practiced on a variety of scales, from hand hoed basins, to animal-drawn rippers, to mechanized no-till seeders.
2. Permanent soil organic cover (at least 30%). This can be achieved through crop residue retention, mulch addition, and green manures/cover crops.
3. Crop diversification through varied crop rotations and intercropping.



CA Plus

Normally, CA practices aren't implemented on their own, but in combination with other good local agricultural practices, which provide greater short-term benefits. CA promoters often refer to this as "CA Plus". For example, in a basin CA planting system, nutrient sources (e.g. manure, compost and/or fertilizers) are often used in greater quantity than conventional practices, and added to the planting basin, where they can be better utilized by the crops. CA systems also encourage optimum plant spacing and precise seed placement. Contour ridges, sometimes planted with perennials, can be integrated into CA systems as an important erosion control method in hilly landscapes. Trees may be planted alongside annual crops in an agroforestry system as another food crop, to provide mulch, and/or fix nitrogen if they are leguminous. In some cases, CA practices open up opportunities for other good practices. Reduced tillage may allow labour to be spread over the off-season and enable farmers to plant earlier, which can improve yields.

It is important to note that a good agronomic practice for one farm in one year may not always work well in other years or in other regions, depending on soil type, topography, weather, and human factors. Scientific studies on the impacts of CA often find contrasting results for this reason. CA tends to work best when farmers are encouraged to experiment and adapt the principles and other practices to their local contexts.

Because CA Plus is often implemented as an integrated system, it can sometimes be difficult to distinguish which practice is producing which effect. Most of the studies reviewed in this guidance note compare one or more strictly CA practices with conventional practice, rather than comparing CA Plus as practiced by farmers with conventional practice as the SUCA soil Health Survey does. It is important to consider both the impact of specific practices, and how they work together when practiced on farms.

SUCA SOIL HEALTH SURVEY

As part of the SUCA program, a soil health survey was conducted on a subset of farms practicing CA in Ethiopia, Kenya, and Tanzania. The survey was designed to be interactive, with farmers actively participating and contributing their knowledge of their own farms. Farmers and technical staff worked together to rate the properties of their soil under contrasting CA and non-CA management. Some of the results of the Soil Health Survey are discussed in this Guidance Note.

Impacts of CA on Soil Health

Soil health describes the capacity of a soil to sustain a healthy plant and animal community, and enhance or maintain water and air quality. Soil health is increasingly recognized as fundamentally important for food production and security, as well as the health of the environment. Healthy soils grow healthy crops, as well as providing other ecosystem services like water filtration and reduced erosion.

Soil Physical Properties

WATER USE & SOIL EROSION

Low rates of water infiltration, high losses of water to evaporation, and resulting low water use efficiency (yield per unit of precipitation) are common problems in degraded soils. Crops grown in soils with poor water infiltration and storage will suffer more during dry spells than those that are able to capture and store more water from rains. Improved soil water properties and reduced erosion are among the most important contributions of CA to soil health and increased yields.

Conservation agriculture practices generally increase water infiltration and reduce runoff compared to conventional practices. Soil and nutrients that would otherwise be lost in runoff, are instead kept on the farmer's field, reducing soil degradation.

Reduced runoff and erosion under CA systems is especially important in high erosion risk areas, such as steeply sloped land. A study in Malawi found higher erosion from ridge till systems compared to conservation agriculture, which led to greater silt and clay content in the CA fields, as these finer particles are preferentially eroded. Higher silt and clay content in sandy textured soils improve soil health properties like water holding capacity and potential for organic matter accumulation. Studies in Sudan and Ethiopia also found reduced soil loss and runoff under reduced tillage and mulching. The study in Sudan did not find an effect of intercropping, indicating that the CA principles of reduced tillage and soil cover are more important than diversification with respect to reducing runoff and erosion, at least over the short term.

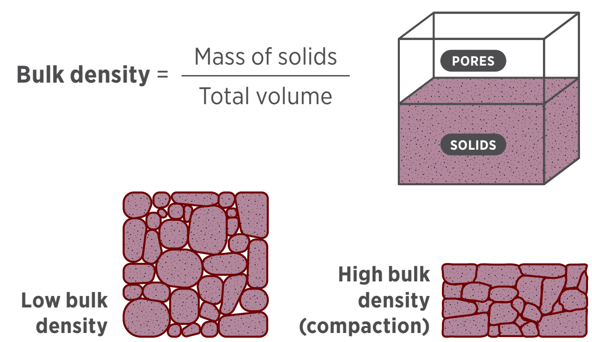
Many studies find higher soil water storage under CA compared to non-CA. Higher water holding capacity of CA soils is often attributed to increased soil organic matter, which acts like a sponge to soak up and store water in the soil. This is very important, as good water infiltration without good storage capacity may not improve crop access to water. For example, a beach sand will have rapid infiltration, but the water will drain away just as quickly, so that the crop cannot use it. In contrast, a soil with high organic matter will hold water in the root zone for the crop to use in the future. Mulch cover may also contribute to higher moisture content by reducing evaporation compared to a bare soil surface, leaving more water available to be used by the crop. Some studies have found that significantly reducing evaporation requires more mulch (8 tonnes/hectare, nearly 100% soil cover) than is usually available in Sub-Saharan CA systems. Thus, many CA fields in this region may not actually experience the reduced evaporation benefit. However, less mulch is required (2 tonnes/hectare, or about 30% soil cover) to increase infiltration and reduce runoff and erosion.

In Ethiopia, farmers in the SUCA Soil Health Survey consistently reported improved water infiltration and water holding in CA fields compared to conventional fields, though results in Kenya and Tanzania were less consistent.

BULK DENSITY

Bulk density is the mass of dry soil per unit of volume. Bulk density of a soil is influenced by its mineral makeup (texture), organic matter content, soil flora and fauna, and compaction history. Healthy soils tend to be lower in bulk density.

Compacted soils, as indicated by high bulk density, have restricted root growth and insufficient pore space for aeration and water storage. On heavily compacted soils, even mulching cannot improve water infiltration. Results comparing bulk density under CA and non-CA systems have been inconsistent. One study from Malawi found higher surface bulk density with a diversified CA system (including cassava, sweet potato and legumes), compared to a maize monocrop, which they attributed to lower residue retention in the diversified system allowing increased raindrop compaction. However, over the long term, improvements in yield in diversified CA systems may increase overall biomass production. Other studies have found no impact, or a positive impact of CA on bulk density. Positive impacts of CA on bulk density seem to be found especially where CA has been practiced for a longer time period.

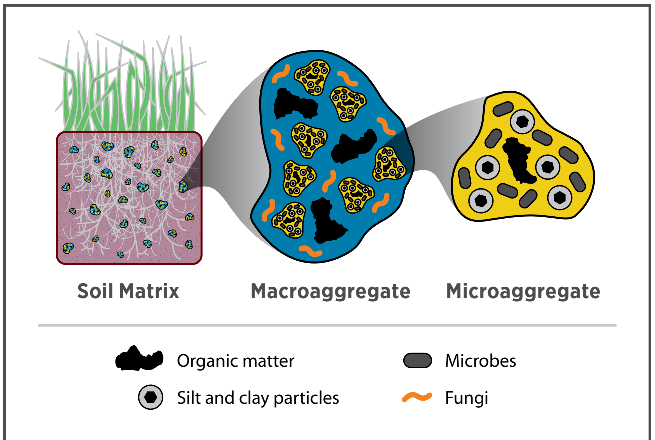


Soil bulk density

AGGREGATE STABILITY

Soil aggregation is the binding together of soil mineral and organic particles, with plant and microbial secretions acting as the glue. Soil aggregate stability is the ability of aggregates to withstand degradation due to wind, water or mechanical (tillage) disturbance, and is considered an important measure of soil health. Good aggregate stability reduces susceptibility to erosion and soil crusting, and improves aeration and water infiltration.

Improved soil aggregation is often linked to inclusion of legume plants in a cropping system, highlighting the importance of the CA principle of diversity. Studies comparing aggregation and aggregate stability in CA versus non-CA fields have been inconsistent. Several have shown more *overall* aggregation in conventional agriculture, perhaps due to incorporation of residues stimulating microbial activity, but improved aggregate *stability* under conservation agriculture. In contrast, the SUCA Soil Health Survey found indications of both increased aggregation and increased aggregate stability in CA soils. Rating of soil structure identified larger aggregate size in most CA soils compared to their conventional counterparts. Reduced soil crusting, which is associated with better aggregate stability, was one of the most consistently reported improvements in all of Kenya, Ethiopia, and Tanzania.



Soil aggregation

Soil Chemical Properties

ORGANIC CARBON

Organic matter is often considered the most important soil health property due to its wide ranging impacts on water infiltration and retention, soil microbiology, soil aggregation, and nutrient cycling. Most studies show increased soil organic matter under conservation agriculture, which can be attributed to all three principles: minimum tillage reduces the break-up of aggregates and exposure of organic matter to oxidation, residue retention adds organic matter directly back to the soil, and diversity promotes healthy microbial communities that can stabilize carbon. Comparing soil organic matter between tillage systems can be difficult because tillage redistributes organic matter deeper within the soil profile. It is important that studies measure to sufficient depths, as well as account for differences in bulk density, when determining soil carbon stocks under CA versus non-CA.

Some studies show a negative impact of CA on soil organic matter, which may be due to a scarcity of nutrients. When additional carbon sources (e.g. mulch) are added to a nutrient-depleted soil, soil organisms may mine soil organic matter for nutrients! This highlights the importance of soil nutrient management through the addition of organic amendments or fertilizer to optimize the benefits of CA.

The SUCA soil health survey didn't directly measure organic matter in the soil, but used soil colour as a proxy. Soils with higher organic matter tend to be darker, and observing changes in soil colour can be an important way for farmers to see the impact of CA. There is substantial variability in soil colour, but soils under CA management tended to be slightly darker than their conventional counterparts.

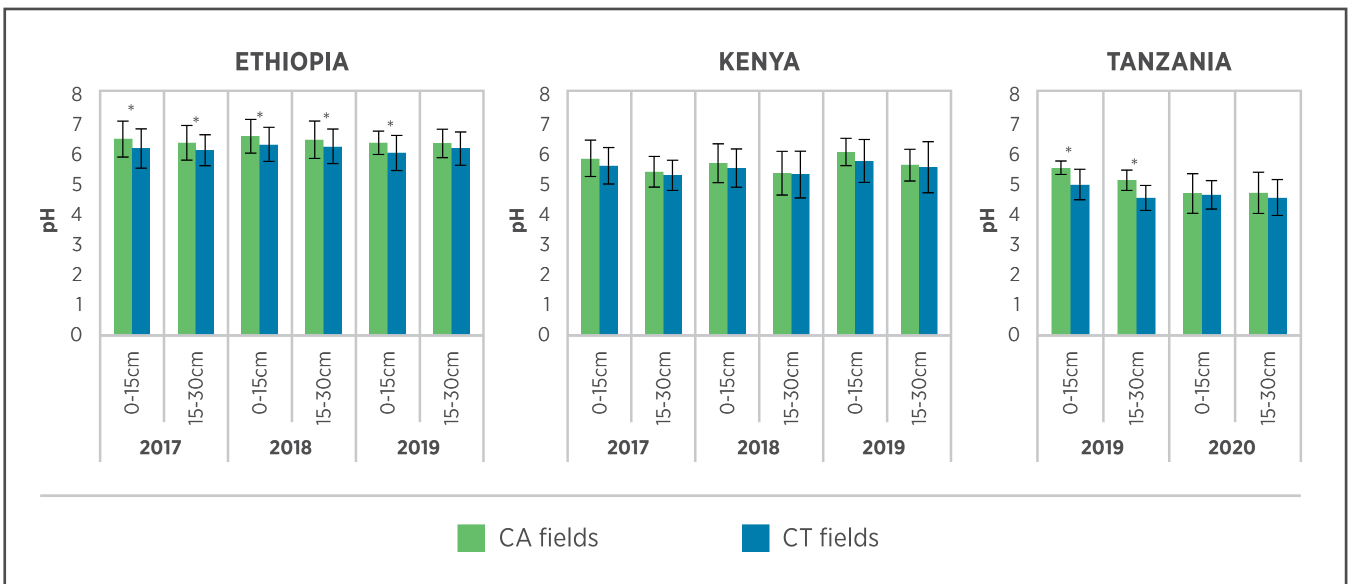


Figure 1. Soil pH data from Ethiopia, Kenya, and Tanzania, comparing CA and CT (conventional) fields. The * represents a statistically significant difference in pH between CA and CT for a given country, year, and depth.

SOIL ACIDITY

pH is an important factor governing plant growth and nutrient availability. In acid soils, with low pH, nitrogen fixation is inhibited, and many nutrients, like phosphorus, are fixed in chemically unavailable forms. Optimal plant growth and nutrient availability occurs in near-neutral soils around pH 5.5-8.0. CA may increase the pH of acid soils by increasing organic matter, which buffers the soil pH and brings it closer to neutral. Some studies have found increases in soil pH with CA, but the results are not consistent. The SUCA soil health survey generally found increased or similar soil pH in CA compared to non-CA fields, with results in Ethiopia and Tanzania showing more evidence of pH increases, while in Kenya the pH was similar between CA and non-CA fields. These data are shown in Figure 1.

SOIL NUTRIENT AVAILABILITY

The CA principle which most directly impacts nutrient availability is that of crop diversity. Legume crops and cover crops add nitrogen to the cropping system. Related CA plus practices, like agroforestry with leguminous trees, also offer nitrogen fixing benefits. In addition, some crop species have special adaptations to access phosphorus and micronutrients, and may help species they are intercropped with to access these essential nutrients as well.

When CA increases organic matter content of a soil this can also have an impact on nutrient availability. Organic matter increases the cation exchange capacity (CEC) of the soil, storing important nutrients like potassium (K^+) and ammoniacal nitrogen (NH_4^+). Higher CEC is associated with better nutrient availability to plants, as nutrients are held in the soil rather than leaching away with the downward flow of water.

Added impact on nutrient availability comes from the CA plus practice of nutrient addition and management. A study in Zimbabwe found higher nutrient availability in the permanent basins of CA planting systems which had received manure compared to conventional fields. While nitrogen can be created by the cropping system via biological fixation, other plant nutrients like phosphorus are at risk of depletion over time if they are not returned to the soil via fertilizers and/or organic amendments. The best agronomic outcomes are achieved when nutrient addition and management is incorporated with CA principles in CA Plus systems.

Biological Properties

MICROBIOLOGY

While physical and chemical properties are the most commonly studied effects of CA, biological properties are increasingly recognized as fundamental to soil health. Many physical and chemical soil properties are the result of microbiological processes- for example, microorganisms promote the formation of soil aggregates and contribute to stabilization of organic carbon.

Preliminary research has shown that conservation agriculture increases soil microbial biomass carbon and nitrogen. Microbial carbon and nitrogen are important for nutrient cycling and carbon stabilization. More research is needed on the impact of CA on soil microbial properties, and their relationships with other soil health properties and crop yields.

The SUCA Soil Health Survey used soil smell as a low-tech proxy for the biological health of the soil, as a rich soil smell is associated with helpful bacteria in the soil. There was some evidence for a richer, “earthier” smell in CA fields compared to non-CA fields.

The soil health survey also used a “Solvita CO_2 burst test” to measure the carbon dioxide produced by soil microorganisms during a given time period. More CO_2 produced indicates greater microbial activity, and may be an indicator of soil health. CA fields in all countries consistently had higher CO_2 production than their non-CA counterparts. Mulching likely plays an important role in high Solvita values, as mulch represents an important food source for the microbial community.

PEST DAMAGE

For many pests and diseases, reduced tillage and crop residue retention as practiced in CA may increase the risk of some crop diseases and pests, as crop residues provide habitat for pests to persist. However, increased diversity and crop rotation can often overcome this challenge by slowing movement of pests from host plant to host plant, and by increasing habitat for beneficial insects.

In Sub-Saharan Africa, fall armyworm (FAW) damage has become a concern for maize growers, and there is some evidence that CA practices may reduce damage. A study in eastern Zimbabwe found that reduced or zero tillage decreased damage from FAW as did frequent weeding. A pumpkin intercrop actually increased the damage, though there was some evidence that a pulse intercrop did the opposite. It is important to remember that complex interactions exist between pest species, crop species, and management practices, so that different CA practices may impact pest species differently.

WEED COMPETITION

As conservation agriculture practices change the soil environment, they also impact weed species. Minimum tillage shifts weed species composition, with more perennial and certain small seeded weeds becoming more prevalent. Many research studies find that in combination with consistent weed control practices, reduced tillage can reduce weed pressure in the long term, as new weed seeds are not brought to the surface and seeds at the surface are exposed to predation. However, weed control, especially in the first few cropping seasons after adoption of CA can require more labour and time, limiting the area that can be managed as CA. In addition, intermediate levels of mulch can increase the germination of some weed species by improving the soil moisture content, though some farmers comment that weeds are easier to pull by hand in a mulched field. Increased weed germination occurs largely at intermediate mulch rates, where sunlight is not fully blocked; very high mulch rates can be as effective as herbicide in managing weeds. Conservation agriculture can be effective over the long term at reducing weed pressure, but only in combination with good weed management practices.

Impacts on Yield

Improvements in soil health have been linked to increases in crop yields in Sub-Saharan Africa, though the impacts depend on many factors such as field size, specific CA methods, length of adoption, soil type, climate, and crop species.

Often, CA is practiced on smaller fields with additional best management practices (e.g. early planting, fertilizer addition, proper plant spacing) compared to conventional fields. When comparing worst conventional practices to CA Plus best practices, yield increases of over 200% are possible. When measuring the effect of CA alone, without other best agronomic practices, moderate yield increases are more common. Yield reductions are also sometimes observed, particularly in the early years after CA adoption. Some meta-analyses evaluating many individual CA studies find that yield improvements increase with time, though others find no such impact.

As part of a survey comparing profitability of CA and non-CA systems, a sample of SUCA farmers recorded CA and non-CA yields in two regions of Ethiopia, four regions of Kenya, and three regions of Tanzania. Despite variation in crops and growing practices across regions, all regions showed greater yields under CA ranging from 23% to 440%, with a median increase of 72%.

Climate and soil type are important factors in predicting where CA will be most beneficial. The greatest impacts of CA occur where precipitation is low and heat stress is high, due to improvements in water infiltration and water-holding capacity associated with CA. In one meta-analysis, sandy soils showed increased yields over a wider range of precipitation and heat stress regimes compared to clay soils, as sandy soils generally have the least capacity to store water. In clayey soils, CA may cause lower yields when precipitation is high due to excess moisture. In contrast, the SUCA soil health survey generally found less consistent improvements in the very sandy Tanzanian soils compared to the loamier soils in Kenya and Ethiopia. The authors hypothesized that extremely sandy soils may have less capacity to build organic matter and improve soil health.

In some regions where precipitation is extremely low (<400mm/year), annual agriculture may not be feasible; pastured livestock may be the best agriculture option in these areas. Regions with 400-1200mm rain per year are usually the best fit for CA. It is important to consider climate and soil type when considering where conservation agriculture will be a best practice.

Conclusions

Reduced tillage, soil cover, and plant diversity work synergistically to improve soil health and increase crop yields in sub-Saharan African conservation agriculture systems. Reduced erosion and improved soil moisture under CA management may be the most important soil health benefits, as many soils in the region are degraded and have poor water holding capacity. Yield increases due to CA are enhanced when combined with other best management practices including nutrient management, erosion control, precision planting, and proper crop spacing.

Stories

EROSION CONTROL AND YIELD INCREASE

CA Plus training began among CFGB-supported Partners in the eastern edge of the Democratic Republic of Congo (DRC) in 2015, and in the ensuing years, soil health, plant health, and crop yields have improved. Many farmers have enthusiastically adopted CA principles, as well as other good practices like contour barriers planted with perennials to prevent erosion. In the community of Bwito, the combination of mulching, contour barriers and virus-resistant cassava has increased average yields from 8.5 tons to 18.9 tons per hectare.

The Chairwoman of a group in the Malyo area, Kambale Masareke, said that in the beginning lots of people were interested in the project because they expected to get free handouts. When they learned that the focus was on education, most of them dropped out. After seeing the health of their first crop, however, people came back wanting to join the group. CA and other soil conserving practices in the DRC have improved soil health, which has in turn improved plant health and yields for farmers!

Kambale Masareke, Chairwoman of a Malyo farmers' group enthusiastically describes the successes of the project. (Photo: Ben Weisbrod)

GREEN MANURE COVER CROPS FOR SOIL COVER AND FOOD SECURITY

Smallholder farmers in Binga, a very dry and hot area of Zimbabwe, have begun to embrace green manure cover crops for soil health and yield improvements, as well as a potential food source for both humans and livestock. Despite the local climatic conditions, pigeon pea and lablab grow well and provide critical soil cover. Initially all farmers preferred non-edible varieties like sunhemp, as they weren't familiar with how to prepare edible pigeon pea and lablab. After an exchange with another community that had been growing and cooking with these green manure cover crops, women shifted to prefer lablab and pigeon pea, while men continued to prefer sunhemp. Green manures can have benefits beyond soil health, and their adoption and spread depends on many factors within a community.

Mrs Mumpande from Binga in her demonstration pigeon pea field (top) and sunhemp (bottom). (Photos: Kulima Mbobumi Training Centre)

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