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Soil carbon in small-holder plantain farms, Uganda
– a comparison between agroforestry and non-agroforestry

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Cover: Agroforestry farm with bark-cloth fig tree and cultivated plantain in Uganda, 2013, photo by author

Abstract

Smallholder farmers in Uganda suffer from declining productivity. With a rapidly increasing population, marginal land is taken into production and the current land management leads to loss in soil fertility and escalation in soil erosion. There are studies indicating that the use of agroforestry increases soil organic carbon (SOC) compared to systems without trees. Soils which are high in carbon have many advantages, for example better water holding capacity, which can reduce stress on crops during drought.

The aim of this study was to determine the effect agroforestry has on SOC concentration in small-holder farming systems in Uganda. The intended system to study was farms practicing agroforestry methods or not in intercropped plantain (cooking banana) fields. The hypothesis was that the practice of agroforestry leads to a higher concentration of SOC. Field work was conducted in Kkingo region, Masaka, Uganda. Ten farms, of which five agroforestry and five non-agroforestry, were selected in cooperation with Vi Agroforestry. At each farm, soil samplings were taken close to a tree and in the middle of the field, respectively, to the mass equivalent depths of 0-20 and 20-40 cm. In total, 40 samples were analysed at Makerere University in Kampala for SOC concentration, water holding capacity, electrical conductivity, pH and texture.

The results showed no significant difference in SOC between agroforestry and non-agroforestry. Other uncontrolled differences between farms and random variation probably masked potential effects of the categories agroforestry respective non-agroforestry. More comprehensive studies with a larger sample of carefully selected pairs of farms would be needed for being able to quantify the impact of agroforestry on SOC.

Sammanfattning

Småskaliga lantbrukare i Uganda lider av produktionsnedgång i jordbruket. En snabbt växande befolkning leder till att utmarker i allt större grad tas i bruk och nuvarande skötselmetoder leder till förluster i markbördighet och ökad jorderosion. Det finns studier som tyder på att agroforestry ger en ökning av kolhalten i marken jämfört med system utan träd. Jordar med högre kolhalt har flera fördelar, som exempelvis en bättre vattenhållande kapacitet, vilket underlättar för grödor att uthärda stress vid torka.

Syftet med denna studie var att undersöka effekten agroforestry har på markens kolhalt i småskaliga lantbruk i Uganda. Systemet avsett att studera var samodlad kokbanan med och utan agroforestry principer. Hypotesen var att agroforestry principerna leder till högre kolhalt i marken än icke-agroforestry. Fältarbete utfördes i Kkingo regionen, Masaka, Uganda. Tio gårdar valdes ut i samarbete med Vi Skogen, varav fem agroforestry och fem icke-agroforestry. På varje gård togs jordprovtagningar nära ett träd respektive mitten av fältet, till mass-ekvivalenta djup på 0-20 och 20-40 cm. Totalt 40 jordprover analyserades vid Makerere Universitetet i Kampala för kolkoncentration, vattenhållande förmåga, elektrisk konduktivitet, pH och textur.

Resultaten visade inte på några signifikanta skillnader i markens kolkoncentration mellan agroforestry och icke-agroforestry. Stor variation i andra brukningsfaktorer mellan gårdar inom respektive grupp samt slumpmässig variation dolde troligen potentiella effekter av kategorierna agroforestry respektive icke-agroforestry. Det skulle behövas mer omfattande studier med ett större antal av noggrant utvalda parade gårdar för att kunna kvantifiera påverkan agroforestry har på markens kolhalt.

Table of contents

Abbreviations

C	Carbon
ESM	Equivalent soil mass
FAO	Food and Agriculture Organization of the United Nations
GDP	Gross Domestic Product
ha	Hectares
ICRAF	World Agroforestry Centre (earlier International Centre for Research in Agroforestry)
SIDA	Swedish International Development Cooperation Agency
SOC	Soil organic carbon
ViAFP	Vi Agroforestry Project

1 Introduction

Uganda has a population of almost 35 million people and the land area (197,100 km^2) is less than half the size of Sweden. The annual population growth rate is 3,32 %, which leaves Uganda amongst the top five fastest growing populations in the world (CIA, 2013). The cultivated areas are not enough to sustain the families' need and farmers start increasingly use marginal land. The marginal areas are for example steep hillsides, valley bottoms, wetlands and forested land (Rusoke et al., 2000). A large part of the population is dependent on agriculture (82 %) and many suffer from food and fuel insecurity (CIA, 2013, Rusoke et al., 2000). The usage of marginal land and the intensive cultivation leads to soil erosion and loss of soil nutrients. Looking historically, data are showing that the productivity of agriculture has declined (Rusoke et al., 2000). Adding to the struggles of smallholder farmers in Uganda, the two rainy seasons are getting more unpredictable due to the climate change. There is a need for sustainable agriculture which can provide food, fuel, fodder, fertility and finance. Agroforestry is the practice of combining trees with crops and/or animals on farms, and is promoted by Vi Agroforestry in Uganda. When the farmers plant suitable trees they can establish sustainable supplies of animal fodder, firewood, food crops, finance and organic fertilizers (Vi-Skogen, 2013). They can also improve the quality of their farmland; the practice of agroforestry has indicated an increase in the fertility of soils, by, amongst other factors, increasing soil carbon concentrations compared to systems without trees (Nair et al., 2009a).

Aim of the study and tested hypothesis

The aim of this study was to determine the effect agroforestry has on the soil carbon (C) concentration in small-holder farming systems in Uganda. The intended system to study was farms practicing or not practicing agroforestry methods in plantain (cooking banana) fields. The hypothesis tested was: The practice of agroforestry will lead to a higher concentration of soil carbon.

2 Background

2.1 Agriculture in Uganda

Agriculture is an important part of Uganda's economy, employing 82 % of the labour and contributing 23.9 % of the gross domestic product (GDP). The most important agricultural products are coffee, tea, cotton, tobacco, cassava (tapioca), Irish potatoes, corn, millet, pulses, cut flowers, beef, goat meat, milk and poultry. Of these the major export crops are coffee, tea, cotton and horticultural products (CIA, 2013). The productivity in agriculture has declined in Uganda, for example banana yields have gone from 8.5 tonnes per hectare to 5.7 tonnes per hectare from 1970 to 1996. This is mainly because of a decrease in soil fertility, increase in soil erosion and pests, and overall poor land-management practices (Rusoke et al., 2000, Vi-Skogen, 2013).

A typical farmer in Uganda is a smallholder farmer who holds around 2 hectare, use simple technology (most commonly land hoe and machete) and applies a minimal amount of inputs such as fertilizers and other agrochemicals. Characteristic is also a lack of access to financial credits and advisory services, which means that the farmers have difficulties in acquiring modern technology and methods. The family is an important source of labour but often it is mainly the women working in the fields. Other problems are recirculation of low-yielding seed varieties, insecure land-tenure systems, dependence of rain-fed agriculture, overuse and overcultivation of the smallholdings, poor and unreliable market access for both inputs and outputs, large herds of livestock leading to overgrazing and high post-harvest losses (Rusoke et al., 2000).

The country can be divided into four agro-ecological zones and depending on these and the farmers' production orientation, Uganda can also be classified in nine different farming systems. The agro-ecological zones are the high-altitude zone producing temperate-zone crops, the pastoral dry to semi-arid rangeland zone practising pastorals systems, the northern and eastern short-grassland zone practising cotton-finger millet-mixed farming systems and the southern and western tall-grassland zone producing perennial and annual crops in mixed farming (Rusoke et al., 2000).

Common perennial crops in the southern and western tall-grassland zone are banana and plantain (cooking banana). These areas have Acrisols and Ferrasols, which are very weathered soils and crop production subsequently depends upon nutrient input to produce high yield. Banana is a huge, herbaceous quasi-perennial with a relatively large request for nutrients and good soil structure. As mentioned above, farmers in Uganda seldom use fertilisers; instead tradition is to use a large amount of organic residues. By applying surface mulch and letting it decompose, nutrients are released and the soil structure is improved. The mulch is a mixture of residues from different crops which banana and plantain are often intercropped with. These are maize, beans, groundnuts, coffee, cassava, potato, yams etcetera (Lekasi et al., 1999).

2.2 Agroforestry

The idea of combining trees, crops and animals on the same land unit is not a new practice; on the contrary it has ancient roots. However it is only for the past three decades it has been recognized by international development associations and the scientific world. It has surfaced as a way to sustain agricultural production in marginal lands and far-off areas not reached by the Green Revolution (Nair et al., 2010). Agroforestry is estimated to cover over 1 billion hectare and to be practised by 1.5 billion farmers worldwide (Zomer et al., 2009). One definition of agroforestry presented by Lundgren and Raintree in 1982 at World Agroforestry Center (ICRAF) is:

> Agroforestry is a collective name for land-use systems and technologies where woody perennials (trees, shrubs, palms, bamboos, etc.) are deliberately used on the same land-management units as agricultural crops and/or animals, in some form of spatial arrangement or temporal sequence. In agroforestry systems there are both ecological and economical interactions between the different components (Nair, 1993).

Depending on their composition, the different kinds of agroforestry systems are silvopastoral (trees and animals), agrisilvicultural (trees and crops), agrosilvopastoral (trees, crops and animals) and others like multipurpose tree-lots, aquaculture with trees, etcetera (Nair, 1993).

In the systems where animals are included, zero-grazing is a common practise. Zero-grazing is a system where the animals are kept in stables and fodder is brought to them (Figure 1). This management practice is gaining popularity especially in parts where areas for free grazing is limited. The zero-grazing practice is considered to increase land productivity, this due to the easier collection of manure that tends to increase the crop yields (Oluka-Akileng et al., 2000).

*Figure 1.*Goat under zero-grazing at Vi Agroforestry's Training Center in Masaka.

Trees can be arranged in different manners in agroforestry systems, either spatial (in space) or temporal (in time), depending on the choice of the farmer. For example hedges give fodder and controls soil erosion while boundary tree planting may serve to demarcate land between neighbours and fallow can be used to restore degraded land (Nair, 1993). Figure 2 shows some examples of how trees and crops can be arranged in agroforestry systems.

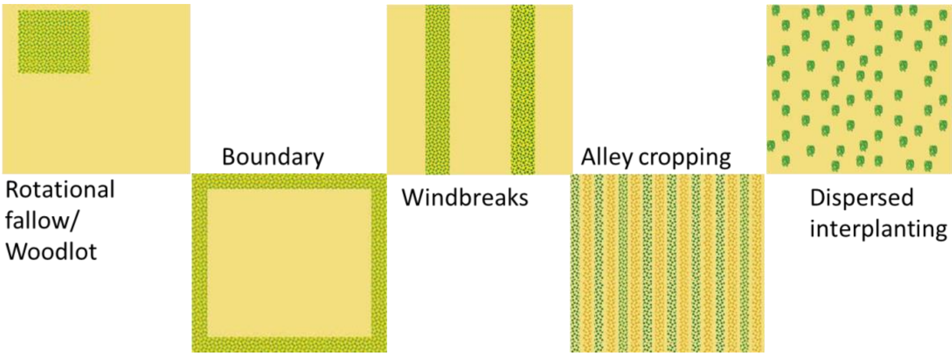


*Figure 2.*Example of how trees and crops can be cropped both spatial and temporal. Source: Nyberg (2013). With permission.

Agroforestry systems are divers and make farmers more able to cope with catastrophic events, such as diseases and natural disasters, as he/she is not relying on one crop only. Trees contribute with litter and mulch, some species can fix nitrogen from the air and roots of trees and shrubs can penetrate the soil deeper than usual crops. Deep roots decrease leaching of nutrients below the main crop root zone as well as perform 'mining' of nutrients and improve soil structure. If trees are planted in the right arrangement, soil erosion can be controlled (Lwakuba et al., 2003, van Noordwijk et al., 2011). Studies have shown that some tree species redistribute water in the soil profile, known as hydraulic redistribution, and thereby prevent soil in the upper layers from drying out too fast. This complementary effect is however dependent upon plant-plant interactions and how wet or dry the soil is, for example the tree-crop mixture may take up more water than is redistributed (Bayala et al., 2008). Trees also have additional benefits and can be used as timber, firewood, fruits, fibres and raw material for medicine. Trees can have the function to regulate the microclimate, by for example acting as windbreaks, and can be used as live fences, and thereby contribute to control land-use (Lwakuba et al., 2003, van Noordwijk et al., 2011).

There are also downsides with trees, they can host pests and diseases and make the field more attractive for insects, birds and/or animals (Lwakuba et al., 2003). If not properly managed, the tree competes with the crop for light, nutrients and water instead of increasing yield (van Noordwijk et al., 2011). This can be avoided by pruning and other management methods, which in its turn can be time-consuming and hard work. Most trees require long time investment, which can be a threshold to the farmers who may need a faster return to their investments. After cutting trees for wood, large stumps makes land preparation difficult. When introducing new species it may thrive in its new habitat and become a difficult weed problem (Lwakuba et al., 2003). Some species are not suitable for agroforestry, like for example eucalyptus, which is highly water-competitive (van Noordwijk et al., 2011).

A wide range of tree species can be used in agroforestry. The design of the agroforestry system is worth thinking through, to recognize what kind of trees function well with the designated crop and what benefits are expected from the trees (Oluka-Akileng et al., 2000). Common trees found inter-cropped on the farms in this study are described below:

Bark-cloth fig/Mutuba (*Ficus natalensis*)

Bark-cloth fig is an evergreen shrub or tree and usually grows to 12 m but may be up to 30 m. The name originates from the practice of making cloth from the bark. Moreover the tree is used as a live fence around homes and for shade in banana, coffee and cocoa plantations where it may increase produce quality (Katende et al., 2000). Bark-cloth fig is expected to improve soil fertility and soil moisture conservation (Oluka-Akileng et al., 2000). The leaves are used for medicine against dysentery and sore throats (Katende et al., 2000).

Avocado (*Persea americana*)

Avocado is a densely leafy evergreen tree which grows up to 10 m or sometimes more. The tree is used for firewood, food, oil, charcoal, shade and cosmetics. The leaves and seeds are toxic for livestock. The fruit is rich in fat, protein and vitamins and is used for food or oil. The root system is close to the surface and very dense, this means that it competes with most crops, although young trees can be intercropped with beans. The fruit gives good money (Katende et al., 2000).

Mango (*Magnifera indica*)

Mango is also a densely leafy evergreen tree, often taking a low rounded form about 10-15 m high. The tree is used for firewood, food, charcoal, bee forage, ornamental, shade, windbreak, soil conservation and gum. The fruits are used for food and are rich in vitamins A and C and gives good money (Katende et al., 2000). The tree may reduce yield of food crops (Oluka-Akileng et al., 2000).

2.3 Vi Agroforestry

Vi Agroforestry (Vi Skogen) is a Swedish development cooperation organisation targeting smallholder farmers in the Lake Victoria Basin in Eastern Africa. Their vision is “a sustainable environment that enables people in poverty to improve their lives”. To achieve their vision, their main strategy is planting trees, which was the original step when working in Kenya to stop desertification. The project has expanded and diversified during the 30 years it has been running (Vi-Skogen, 2011). Nowadays, Vi Agroforestry is a broader concept and the work areas identified for the period 2013-2015 are sustainable agriculture adapted to climate change (based on agroforestry and the right to food), strong farmer organisations, gender equality and economic security (Vi-Skogen, 2013).

The organisation is non-profit and non-governmental; funding is received from direct donations, fundraising activities and the organisations biggest financier the Swedish International Development Cooperation Agency (Sida). Cooperation with companies is becoming more important, and the organisation wants to increase the selling of climate compensation to companies (Vi-Skogen, 2013).

The cooperation works in Kenya, Tanzania, Uganda and Rwanda. In Uganda, the Vi Agroforestry project started 1992 and has been through the same development and diversification as the rest of the organization. The areas of the project are concentrated around Kampala and Masaka. An important principle of Vi Agroforestry is to make the areas they work in independent by building networks. When it is time, Vi Agroforestry steps back and the area is self-sufficient in for example providing tree seedlings and financing systems (Figure 3) (Vi-Skogen, 2011). In the Masaka area, Vi Agroforestry participated in forming Kkingo farmers' cooperative (Tamale, 2010).

*Figure 3.*Nursery at Vi Agroforestry's Training Center in Masaka.

2.3.1 Kkingo farmers' cooperative

The cooperative is located in Kyangoma village, Nkoni Parish, Kkingo sub-county in Lwengo District. The cooperative started at the end of the Vi Agroforestry Project, in July 2007. The cooperative first consisted of 124 farmers but has grown and today holds around 900 members. By forming a cooperative the farmers have more power in bargaining, planning and marketing. Their activities involve enterprises such as dairy cattle rearing for milk production, banana plantations and coffee farming, tree planting, community savings empowerment (CO-SAVE), etc. They affect these enterprises by offering services: agricultural extension, financial service (CO-SAVE), artificial inseminations (AI) and collective marketing of farm produce and procurement of farm inputs. The cooperative collaborate with organisations such as East Africa Dairies Development Program (EADDP), Send a Cow and Vi Agroforestry (Tamale, 2010).

The agricultural techniques that the cooperative promotes is land management practices such as compost preparation and application in order to improve soil fertility, construction of trenches to trap water to secure water availability and soil erosion control by using crop residues as trash lines and building terraces. The tree-growing is made easier by having a tree nursery which provides the members with seedlings at subsidized prices. The trees are planted in agroforestry systems including hedge planting (mostly with *Calliandra*), boundary tree planting, dispersed planting to provide shade to coffee, planting around compounds and measurements for firewood conservation (Tamale, 2010).

2.4 Soil carbon

The concentration of carbon in the soil is the result of the input of new organic material and the decomposition of new and old material. Changes in soil carbon concentrations are slow; the effects of changed land-use can only be seen after a long time. This is due to the fact that the largest part of the carbon occurs in stable forms and has a very slow turn-over; new input of organic material (like leaves or straw) gives a very small contribution in comparison to the total stock of carbon. For example, the new input often represents only one or a few percent of the carbon stock. Therefore, even though its turn-over rate is fast and changes in the fresh C stocks are faster the rate of total soil C stock change is mostly determined by the stable forms. An expected increase or decrease in carbon concentrations after changing soil/crop/farm management may therefore take many years before changes are measurable (Eriksson et al., 2011).

Soil organic carbon (SOC) plays an important part in biological, chemical and physical processes in the soil. It also is the main source of energy for most of the soil organisms which aid the release of plant available nutrients when the organic matter is decomposed (Eriksson et al., 2011). The soil organic matter and microorganisms also contribute in buffering pH, help soil aggregation and degrade pollutants and pesticides. SOC also adds to the soils cation exchange capacity and water holding capacity, which is important especially in sandy soils. Soils which are high in carbon have many advantages, for example better water holding capacity, which can reduce stress on crops, like for instance during drought (Paterson and Hoyle, 2011).

There is a positive correlation between carbon and clay content, for example clay soil with 50 % clay have a minimum concentration of organic matter that is twice as high as in sandy soil with a small amount clay (Eriksson et al., 2011). This is partly because the clay particles and the organic matter bind strongly to each other and increase soil aggregation, so called organo-mineral complexes. The organic matter becomes spatially inaccessible or difficult to access for the decomposing soil organisms which lower the turn-over rate. Another important factor which has a great impact on the soil carbon concentration is climate (Eriksson et al., 2011).

2.5 The effect of agroforestry on soil carbon

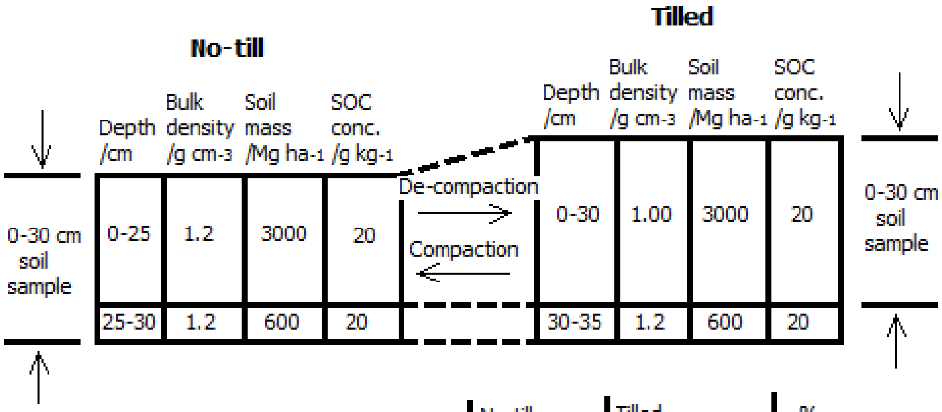
As the trees are growing in the agroforestry system they sequester carbon; bind carbon in their biomass and influence the carbon storage by litter fall and decay, fine root dynamics, organic matter turn-over, deposition in the rhizosphere and formation of soil aggregates and organo-mineral complexes (Nair et al., 2010). If external effects such as wind or steep slope are absent, individual trees affect the soil in a manner of symmetry; the highest impact is seen under the crown canopy and declines outward. Phenomena like this have been called “islands of fertility” or “resource islands”, with a microenvironment which leads to a positive loop for the establishment and productivity of new vegetation (Zinke, 1962).

An estimated potential for total C sequestration in agroforestry systems is between 12 and 228 Mg C ha^{-1} (Albrecht and Kandji, 2003). The variation largely depends on the kind of agroforestry system put in place. The structure and function are often determined by environmental and socio-economic variables, but also tree species and system management influence the carbon storage.

Research indicates that when combining trees, crops and/or animals in an agroforestry system more carbon is generally sequestered, compared to non-agroforestry. Nair et al. (2009a) summarized 12 reports on soil carbon-sequestration potential under agroforestry systems and shows an overall ranking in SOC content where forest > agroforests > tree plantations > arable crops. Because the reports were selected in order to cover a broad spectrum of agroforestry systems in different geographical areas, the sizes of soil carbon stocks in the reports vary greatly depending on the variation between the systems, ecological regions and soil types: e.g. from 6.9 to 302 Mg C ha^{-1} (0-100 cm) or 45 to 162 Mg C ha^{-1} (0-40 cm) (Nair et al., 2009a). A fixed sampling depth was used in these studies, and changes in bulk density were not taken into consideration (Amézquita et al., 2004, Haile et al., 2008, Kirby and Potvin, 2007, Makumba et al., 2007, Oelbermann et al., 2006, Parrotta, 1999, Peichl et al., 2006, Sharrow and Ismail, 2004, Swamy and Puri, 2005, Takimoto et al., 2008).

2.6 Strategies to study soil C stocks

In most literature SOC is quantified to a fixed depth, calculated as the product of SOC concentration, bulk density, and depth. Historically this has been the main practice and is, among others, adapted by Intergovernmental Panel on Climate Change (IPCC) and the European Union (EU). However Wendt and Hauser (2013) argue, as do several researchers, that the fixed depth method is inaccurate. Considerable errors have been shown when using the method, due to the fact that soil bulk density can differ between treatments like till or no-till, different land-use systems or changes during a monitoring period. When for example comparing tillage and no-tillage at a depth of 30 cm, tillage to a depth of 25 cm may lead to a change in bulk density from 1.20 to 1.00 g cm^{-3}. The soil thus occupies 30 cm instead of 25 cm after tillage, this means that the soil with tillage has less soil mass to be analysed for SOC (see Figure 4). In order to avoid these errors, Wendt and Hauser are instead promoting equivalent soil mass (ESM) to quantify SOC. This method is based on fixed soil mass layers with given reference mass (Wendt and Hauser, 2013) as further explained below.



	No-till (compacted)	Tilled (de-compacted)	% error
SOC (kg ha^{-1}) in 30 cm depth layer	72 000	60 000	-16.7
kg SOC ha^{-1} in 3000 Mg soil mass layer	60 000	60 000	0
kg SOC ha^{-1} in 3600 Mg soil mass layer	72 000	72 000	0

Figure 4. Example of error fixed depth creates when soil bulk density differs. Created after: Wendt and Hauser (2013).

3 Materials and methods

This study included soil sampling and analysis. Field work was carried out in the Kkingo region, Uganda. Soil samples were taken between 11th of April and 10th of May 2013. Samples were collected from 10 farms with continuous intercropped plantain, five of these practiced agroforestry as identified by the Vi Agroforestry extension officer and the board of Kkingo farmers' cooperative. Agroforestry had been implemented since 1995. Vi Agroforestry left the area 2006 but the farms were still implementing agroforestry. Laboratory analyses were conducted at Makerere University, Kampala, Uganda.

3.1 Study site

The Kkingo region (S 00°20', E 031°37') is located 15 km west from the town Masaka, in the southern part of Uganda. 30 km in the other direction from Masaka is Africa's largest sea, Lake Victoria. The climate is warm and humid with a mean annual temperature of 17 °C and an average annual precipitation of 1332 mm (World Weather Online, 2013). There are two rainy seasons, the first one is between March and May and the second one is from September to November (CIA, 2013). Most rain falls in April (282 mm) (World Weather Online, 2013).

Figure 5. Uganda. Source: About.com.

The soil is medium textured and the soil orders are Ferric Acrisols and Orthic Ferrasols (FAO-Unesco, 1974, FAO-Unesco, 1977). The terrain in Uganda is dominated by a plateau with a rim of mountains, and around Masaka the altitude is between 1200-1300 m.a.s.l. (CIA, 2013). The slopes in the area are according to FAO classification both a- and b-class, which are level to gently undulating (0-8 percent) and rolling to hilly (8-30 percent), respectively (FAO-Unesco, 1974). The area belongs to the southern and western tall-grasslands zone and the farming system is intensive banana-coffee-lake shore system (Rusoke et al., 2000).

3.2 In situ

3.2.1 Identification and description of sites

Ten farms were selected after communication with Vi Agroforestry and the farmers as well as observation for certain characteristics. The study was carried out in collaboration with two other studies; therefore the farms were chosen to suit all demands. Criteria for the farms were to have approximately the same soil type (preferably 25-30 % clay) and to grow plantains. The agroforestry farms were requested to have agroforestry trees planted in a dispersed manner and to practice mulching. The non-agroforestry farms also had trees in their fields, but less and not managed by agroforestry methods. There were no nitrogen fixing trees on any of the farms, but three farms had beans intercropped. All farms had animals but the agroforestry farms were implementing zero grazing whereas the other farms had free grazing. The animals were cows, pigs, goats and chickens, in varied size of herds (see Table 1). Truly paired farms could not be found; however as similar micro-climate as possible was obtained for all farms by selecting farms within the same area (see Figure 6). GPS coordinates (including elevation) were noted. At each farm two sites were selected for soil sampling, one in the middle of a field and one close to a tree (as affected as possible by agroforestry). This was done in order to get as similar degree of disturbance and sun radiation as possible for the two groups of samples. Photo documentation was done for all field activities. Individual information for each farm can be seen in Table 2.

Table 1. *Average (range) acreage, banana yield and numbers of cows, goats, pigs and hens (n=5). Data derived from semi-structured interviews by Andersson (2013)*

Average	Agroforestry farms	Non-agroforestry farms
Acreage (ha)	2.0 (0.8-2.4)	1.7 (0.4-2.4)
Banana yield (kg ha^{-1} $season^{-1}$)*	680 (200-1600)	558 (120-1600)
Cows	2.8 (2-4)	3.4 (0-17)
Goats	5.2 (0-10)	0.6 (0-2)
Pigs	5.4 (0-17)	0.8 (0-4)
Hens	47.4 (7-150)	1.6 (0-4)

*Generally two seasons per year

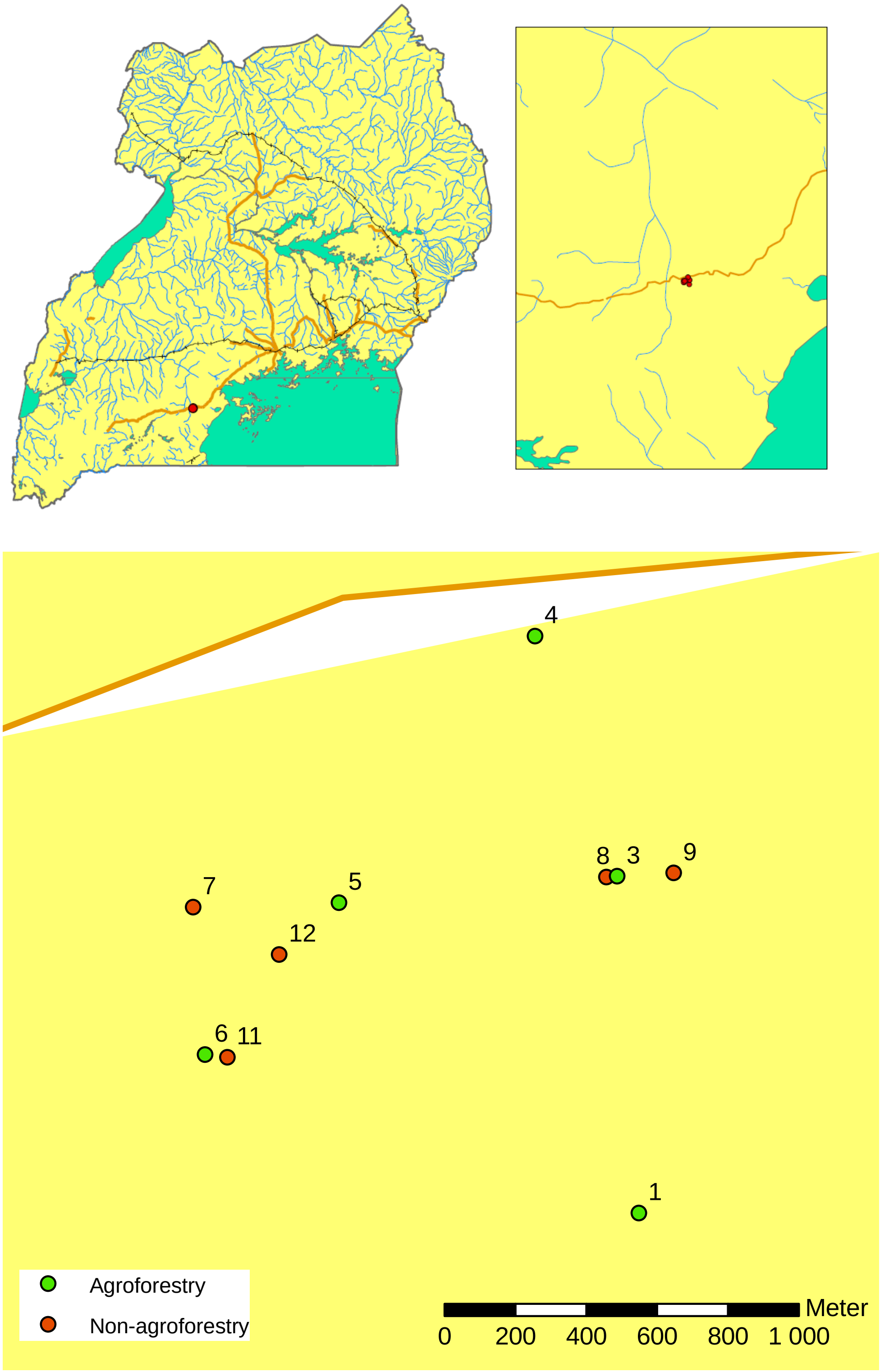


Figure 6. Overview of the location of the farms. Graphics: Anders Larsolle, SLU. With permission.

Table 2. *Information about the farms*

Farm*	Practice	GPS coordinates	Elevation (m.a.s.l.)	Area (ha)	Trees	Plantain inter-cropped with	Animals	Spreading manure
1	Agroforestry	S 00°21.163’, E 031°37.734’	1223	4.9	Bark-cloth fig	Beans, coffee, elephant grass	1 cow, 1 pig, 1 goat, 8 chickens	Dung used for bio-gas, then spread
3	Agroforestry	S 00°20.651’, E 031°37.701’	1279	0.8	Avocado	Cassava, pumpkin	3 cows, 17 pigs, 7 chickens	Sells manure
4	Agroforestry	S 00°20.286’, E 031°37.576’	1235	2.4	Avocado	Coffee	3 cows, 10 pigs, 10 goats and 150 chickens	Digs down the ma-nure
5	Agroforestry	S 00°20.691’, E 031°37.278’	1251	2.2	Avocado	Sugarcane	2 cows, 25 chick-ens	
6	Agroforestry	S 00°20.922’, E 031°37.074’	1258	2.4	Bark-cloth fig	Beans, jams	2 cows, 10 goats, 10 chickens	Recently spread manure
7	Not agroforestry	S 00°20.698’, E 031°37.056’	1183	1.6	Avocado	Coffee, irish potato, jams, cassava	4 pigs, 8 chickens	
8	Not agroforestry	S 00°20.652’, E 031°37.685’	1275	0.4	Bark-cloth fig	Beans	4 chickens	Buys manure
9	Not agroforestry	S 00°20.646’, E 031°37.787’	1241	2.2	Avocado	Coffee	2 goats	Buys mineral fertiliz-er to maize. Manure around coffee
11	Not agroforestry	S 00°20.926’, E 031°37.108’	1174	2.4	Bark-cloth fig	Coffee, jams	2 pigs, 1 goat	
12	Not agroforestry	S 00°20.770’, E 031°37.187’	1231	1.2	Mango	Pumpkin, jams	17 cows	No manure in the plantain field

* The numbers given to the farms are the same as in Andersson (2013). Farm 2 and 10 are excluded in this study.

3.2.2 Soil sampling

In order to capture an equivalent soil mass layer representing approximately 40 cm of soil, six cores in each field were taken to 40 cm depth (3 cores per sampling plot) using a soil auger. To decide the reference sample mass an average weight of the samples was calculated after drying and weighing each core.

At each sampling plot eight new samples were subsequently taken to a total depth of 48 cm. The cores were taken from 3 layers (0-16, 16-32 and 32-48 cm). The eight samples from each sub-layer were pooled, dried and stored in plastic bags (Figure 7).

Figure 7. Field work; left: emptying auger, right: example of depth 0-16.

3.2.3 Preparation of samples

Figure 8. Preparation of samples by sieving at Makerere University.

Soils samples were analysed at Makerere University, Kampala. In Kampala the samples were left to further air-dry for about two days and then crushed manually before sieving through a 2 mm sieve (Figure 8). The depth layer 0-16 was topped up to ½ of the reference sample mass (601 g), using soil from the 16-32 cm layer. The remaining mass from the 16-32 cm layer was then topped up to half of the reference soil mass using the sample from 32-48 cm layer. In all cases correction for gravel content was made. What was left of the last depth layer (32-48 cm) was discarded. This gave 40 samples with the equivalent soil mass depth layers corresponding to on average 0-20 and 20-40 cm, hereafter named depth layers 0-20 cm and 20-40 cm.

3.3 Soil chemical and biological analyses

Organic carbon concentration was determined by using the Walkey-Black method (Walkey and Black, 1934) with the addition of external heating as modified by Nelson and Sommers (1975). The carbon was oxidized by a mixture of aqueous potassium dichromate ($K_2Cr_2O_7$) and sulfuric acid. After heating, the samples were titrated with ferrous ammonium sulfate against the residual $K_2Cr_2O_7$. From the volume titrated, organic carbon was calculated (Figure 9)(Okalebo et al., 2002).

Figure 9. Titration with ferrous ammonium sulphate at Makerere University.

The hydrometer method was used in order to analyze the soil particle distribution of the top layer (Okalebo et al., 2002). The content of sand, silt and clay was determined as a percentage by weight of oven-dry and organic matter-free soil. Soil pH was measured in 2.5:1 deionized water to soil suspension using a pH-meter (Okalebo et al., 2002). Electrical conductivity was performed on saturated paste extract using a conductivity meter (Okalebo et al., 2002). The water holding capacity was calculated as the moisture content of a freely drained soil sample and expressed per dry matter soil (Okalebo et al., 2002).

3.4 Statistical analysis

The data was analysed statistically using box-plots and analysis of variance testing the main effects of agroforestry vs. non-agroforestry management, near tree vs. middle of field, and depth and their interactions. Sampling spot was used as random factor to account for autocorrelation between top and bottom section of soil cores (confidence level 95.0) (JMP 10.0.2, SAS Institute Inc., Cary, NC, USA).

4 Results

4.1 Total C

The null hypothesis was proved; there was no significant difference in soil carbon for any of the depths between agroforestry and non-agroforestry (see Table 3). Since equivalent soil mass was sampled the same relations were valid for the amounts of soil carbon within each depth layer. When the amounts of soil carbon were summed over the whole depth (0-40 cm), there were also no significant differences between production systems nor sampling locations (results not shown).

The only significant result was that the carbon concentrations declined with depth (p-value < 0.0001) (see Table 3).

4.2 Texture, WHC, pH and EC

The soils were similar in texture, water holding capacity, pH and electrical conductivity; no significant difference could be found (see Table 3).

Table 3. *Average (std) content of clay, silt and sand, water holding capacity (WHC), soil carbon concentration (in percent of air-dried soil), pH and electrical conductivity (EC) in agroforestry and non-agroforestry soils. P-value for comparison of agroforestry vs. non-agroforestry, close to tree vs. middle of field and 0-20 vs. 20-40 cm (n=5)*

			Clay (%)	Silt (%)	Sand (%)	WHC (%)	C (%)	pH	EC (µS/cm)
Agroforestry	Near tree	0-20	33.6 (8.4)	15.2 (5.7)	48.6 (5.8)	32.4 (6.8)	1.5 (0.2)	7.3 (0.9)	142.5 (20.9)
		20-40				29.3 (8.1)	1.0 (0.2)	6.9 (1.3)	115.2 (31.1)
	Middle of field	0-20	30.5 (10.6)	14.0 (4.2)	53.2 (9.1)	31.5 (8.2)	1.4 (0.2)	7.4 (1.3)	242.5 (174.3)
		20-40				31.5 (1.2)	0.9 (0.2)	7.1 (1.7)	148.3 (126.4)
Non agroforestry	Near tree	0-20	29.4 (7.1)	17.1 (6.7)	52.8 (6.0)	32.5 (2.6)	1.7 (0.2)	7.0 (1.2)	126.1 (43.3)
		20-40				28.0 (5.0)	1.0 (0.2)	6.6 (0.9)	75.2 (44.6)
	Middle of field	0-20	30.8 (8.9)	14.7 (4.4)	53.5 (6.1)	32.7 (7.2)	1.4 (0.2)	7.1 (0.9)	114.8 (46.1)
		20-40				31.6 (4.7)	1.1 (0.1)	6.8 (0.6)	79.5 (45.9)
P-value									
Agro vs. non agro	0-20		ns*	ns*	ns*	ns*	ns*	ns*	ns*
	20-40					ns*	ns*	ns*	ns*
Near tree vs. middle of field	0-20		ns*	ns*	ns*	ns*	ns*	ns*	ns*
	20-40					ns*	ns*	ns*	ns*
0-20 vs. 20-40						ns*	<0.0001	ns*	ns*

* not significant

5 Discussion

The hypothesis tested was if there were any differences in soil carbon concentrations between agroforestry and non-agroforestry in small-holder plantain production. The results did not show any significant differences in soil organic carbon concentrations between agroforestry and non-agroforestry farms in this study. In view of earlier indications that agroforestry may increase soil C concentrations (Nair et al., 2009a) the results may suggest that the smallholder plantain production systems of the area have high C sequestering capacity irrespective of whether agroforestry methods are deliberately applied or not. However, it may also be that high data variability masked potential differences in this small study, or that differing sampling methodologies make the studies difficult to comparable.

5.1 Limitations of the study and possible improvements

A low level of difference in complexity between the systems studied

The complexity of the non-agroforestry farms was underestimated when selecting the farms. All the farms had trees on their farm and a lot of intercropping. The intercropped crops were often perennials, usually coffee. The main characteristic that distinguished the agroforestry farms were that they had more trees and larger variation in species (agroforestry 10 species/farm while non-agroforestry had 1-2 species/farm) (Andersson, 2013). Agroforestry farms practiced zero grazing and to a varying degree also some of the agroforestry methods, e.g. trash lines and compost preparation. From interviews made by Andersson (2013), it was clear that all farmers in the study had started using agroforestry eighteen years ago but that some had stopped; this added to the fact that the differences in system characteristics were small.

The tree species in the study varied between the farms, there were bark-cloth fig, avocado- or mango trees but no nitrogen fixing trees. However, the distribution of tree species by which sampling was done was similar between agroforestry and non-agroforestry in the study. The effect of agroforestry would probably have been clearer if the agroforestry farms had had nitrogen fixing trees which could have increased the productivity in a long-term perspective. Other nitrogen fixing plants, legumes, were grown by some farmers this year (farm 1, 6 and 8 had beans), but it was possible that the other farms had legumes earlier years.

Therefore, more care should have been taken in the selection of farms, so that more distinctly different groups were created.

Differences in sampling strategy

Originally the intention was to sample whole cores with the auger. After trying to do so at the first farm, and failing, the rest of the sampling was performed in steps. Doing so there was a risk of getting soil from the upper layers into or at the surface of the core sampled from the bottom layer. This was avoided by making sure that only 16 centimeters were in the core and by controlling the color of the sample to make sure that darker soil (with higher content of soil carbon) from the top layer was not included.

The error potentially induced by differences in bulk density was avoided by using the equivalent soil mass method. The bulk density was for example expected to be affected by the difference in soil tillage/management/hoeing, since the soil in the middle of the field was likely to be more tilled than the soil below the trees. In the studies presented in Nair et al. (2009a) all researchers used a fixed depth method. The difference in soil sampling methods may partly explain differences between this study and earlier studies.

Background noise

Generally there was a high level of background noise since the numbers of paired farms was fewer than intended, only farm 6 and 11 and 3 and 8, respectively, were bordering to each other. This was probably of greater importance for the results since the study was small.

Other confounding factors

There were individual differences between the farms that may be assumed to contribute to the data variability. For example, farm number 12 had the highest soil carbon concentration value and was seen as economically richer than the rest. The farmer had a lot of cows (17) but claimed that not much of this manure was spread at the field of sampling. However, it might still have contributed to the higher soil carbon concentration (see Figure 11, Appendix). Another individual difference was the size of the trees; at farm 3 the tree by which sampling was done was considerably smaller compared to the other trees in the study. The bigger and older trees should have higher potential and more time to add to the soil organic matter than the smaller ones (Nair et al., 2009b).

At some of the farms the location ‘close to a tree’ was in the outer parts of the field, with less management (e.g. compost inputs) by the farmer compared to ‘middle of field’. This may have led to the background soil carbon concentration being lower in the outer parts of the field compared to closer to the homestead. Even though there was an effect from the tree, this might not have been visible in the result since there were not equal conditions. A gradient of soil carbon and soil fertility within a farm have been seen in earlier studies, varying with the distance to the homestead, soil properties and the management of the farmer (Vanlauwe et al., 2006).

The use of compost and manure was expected to give the agroforestry farms an advantage compared with non-agroforestry farms. Due to this, the zero-grazing management applied at the agroforestry farms was thought to contribute to the agroforestry hypothesis. The easier collection (and use) of manure could have shown as an increase in soil carbon concentrations in favor for agroforestry. Unfortunately the practice at the non-agroforestry farms was to bind the animals to trees, which occasionally had been the same trees that were in the study. Another aspect was the overall management of the manure. This was not covered during storage which probably led to losses of nitrogen and other nutrients, and thus to decreased fertilizer value and carbon input via crop production, hence decreasing the potential differences between the systems.

There could also have been higher general levels of plant-available nitrogen in the plantain fields than expected. Research has shown evidence of nitrogen fixing bacteria in association with banana roots (Mia et al., 2010, Nyambura Ngamau et al., 2012, Souza et al., 2013). If there were nitrogen fixing bacteria in association with the plantain in this study, the effect of the addition of nitrogen through legumes and manure would have been relatively less operative for the biomass production and hence the carbon flow to the soil.

Another contributing factor could be the slow changes in soil carbon after change of land management, but the agroforestry systems had been in place for eighteen years. With the warm and humid climate in Uganda changes in incorporation of new organic material in the carbon pool should be measurable.

The hypothesis that agroforestry led to an increase in soil carbon concentrations compared to non-agroforestry was not supported. However, all these factors of variability considered made the results unreliable and did not give certainty for the conclusion that no changes had occurred.

5.2 Future work

The choice of the farms involved is of great importance as could be seen in this study. In order to study changes between agroforestry and non-agroforestry the farms need to be considerably different in farm management, while very similar regarding e.g. clay content and location. Considering sampling methods, there is a need to promote ESM instead of fixed depth methods in order to be able to compare between different management/land use/over longer periods of time. The ESM method is a suitable routine if another study would want to investigate the changes in soil carbon over time. Soil-sampling depth should be increased to go beyond the surface soil, in order to make relevant comparisons and be able to see the effect agroforestry have on the deeper soil horizons.

It would have been interesting to measure the yield of the crop in the vicinity of the trees in correlation to the distance from the trees; to see the total effect of the tree. This would have required a crop which covered the ground more homogenously and which matured at the same time, like maize. Another aspect is the nitrogen content, which would have been interesting to measure in order to tell more about the effect of the manure applied. Information about both carbon and nitrogen inflows would have made it possible to tell more about the possible mineralization or assimilation of carbon.

Both the studied systems in this study had minimum tillage and a lot of intercropped perennials; this is something that might become less common in the future Uganda. If the standard of living increases and labor becomes more expensive agriculture may become more mechanized. The highly weathered soils, climate and terrain of Uganda might make it difficult to retain soil fertility and avoid soil erosion. It is therefore important to better understand the effect and contribution of agroforestry systems to soil fertility in order to evaluate the most likely effects of transmission into mechanized monoculture.

6 Conclusion

Since the farms included in this study were few, it is difficult to draw any general conclusions. The results suggested no significant difference in soil organic carbon concentrations between the agroforestry and non-agroforestry farms. However with all sources of errors and variability considered a conclusion cannot be formed on these results, especially as they contrast with a number of more comprehensive published studies. If the study was to be done again, more care would be taken in selecting larger amount of paired farms. The farms in this study did unfortunately not have a profound difference in management.

Other uncontrolled differences between farms and random variation probably masked potential effects of the categories agroforestry respective non-agroforestry. More comprehensive studies with a larger sample of carefully selected pairs of farms would be needed for being able to quantify the impact of agroforestry on SOC.

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Appendix

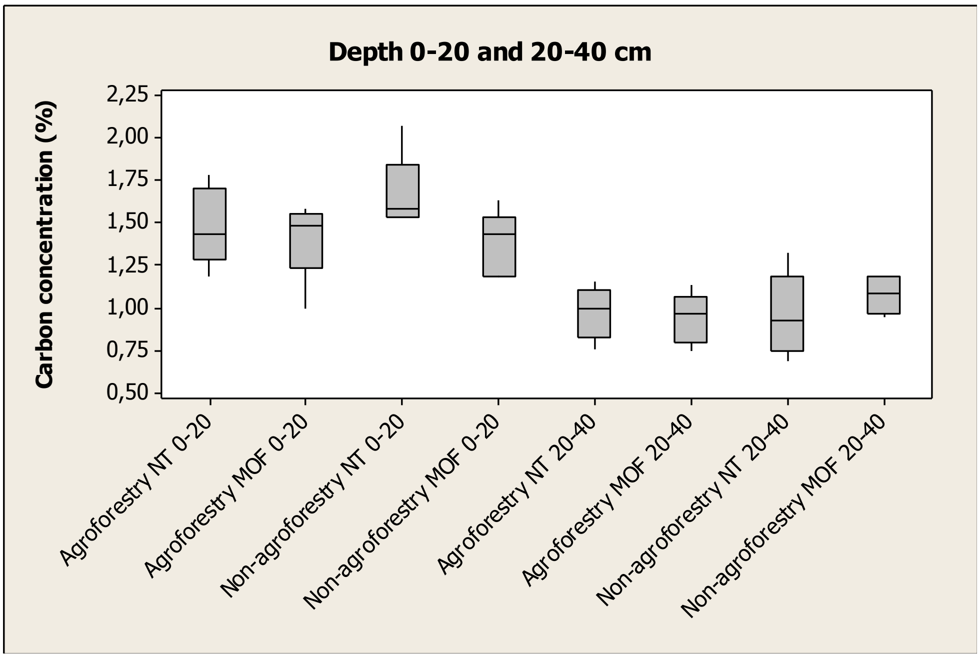

Figure 10. Boxplots showing the distribution of the data for each combination of management, field location and depth (n=5).

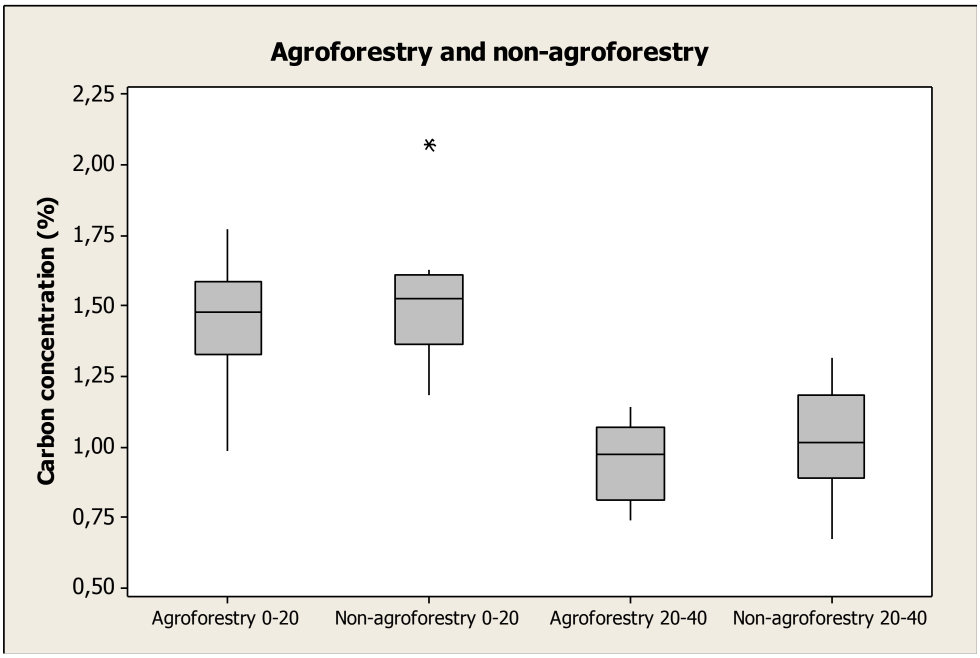

Figure 11. Boxplots showing the distribution of the data for the two land-management-types grouped into depth 0-20 and 20-40. The asterisk shows an outlier sample at farm 12.