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A way out of food insecurity and poverty

– The potential of using fly larvae composted faeces as organic fertiliser in sub-Saharan Africa agriculture

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-The potential of using fly larvae composted faeces as organic fertiliser in sub-Saharan Africa agriculture

En väg ut ur osäker livsmedelsförsörjning och fattigdom
-Potentialen att använda fluglarvskomposterade fekalier som organiskt gödningsmedel i subsahariska Afrika

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Foreword

Growing up in an area totally surrounded by farms, and going to a boarding school in the middle of nowhere, and also surrounded by farms, all I "knew" was agriculture. Even though I did not understand anything about it, I could notice some of the issues that farmers were facing, erratic rainfall and pests amongst other things. Apart from these issues, I realised that most of the countryside in Zimbabwe was continuously losing its tree cover due to deforestation as farmers cut down trees for curing tobacco. Land degradation was growing at a massive scale, unabated, and I wondered why farmers were destroying their resource base. This prompted me to take up a Bachelor's in Bio-protection of Agricultural Systems and the Environment. In my bachelor's studies, every problem had a solution and I was really determined to solve the problems my country was facing.

Unfortunately or fortunately I found myself in Sweden, studying a master's in Agroecology, it was only then that I realised things were not as simple as I thought. Being enlightened that agriculture was not merely agronomy, but a complex system that encompasses society, economy, ecology and politics, I was extremely overwhelmed. For a while, I was very disappointed that I had become aware of this complexity, because it had destroyed all the ambition I had to solve agricultural issues back home. However, I later on embraced this complexity, and started looking at things holistically and now I understand that there are a lot of factors that influence how agricultural systems function.

My ambitions to solve problems have not been lost, but they have been enhanced through this program. Being aware of the complexity and messiness found in agricultural systems, I am now prepared to deal with the problems involved. In this thesis, I am trying to solve a complex problem, thanks to systems thinking, I am now able to take into account of the various system components and their interrelationships that are important to focus on in order to solve such a problem.

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Thabani E. S. Chirere.

Abstract

Chronic food insecurity in Sub-Saharan Africa (SSA) has become an issue of major concern. An estimated minimum of 25 % of the population suffers from malnutrition, and thousands of people die of hunger everyday. Food insecurity in SSA has been attributed to the fact that 75% of the region's soils are nutrient deficient, mainly due to nutrient mining. An increasingly growing population has had to face a decreasing agricultural production resulting in food insecurity. Currently, some methods to replenish soil nutrients are being used, including crop rotation, application of animal manure as well as mineral fertilisers. However, these methods have not been sufficient to address the issue of soil nutrient depletion. The aim of this study was to 1) investigate the potential of using black soldier fly (BSF) composted human faeces as a fertiliser for use by smallholder farmers in SSA; and 2) to investigate the perceptions held by people from Africa regarding the use of human faeces in agriculture. The Social-Ecological Systems Framework was used to guide the study; and hard and soft systems methodologies were employed in support of the framework. Pot trials were carried out in the greenhouse using Swiss chard (*Beta vulgaris*) to investigate the effect of black soldier fly larvae composted human faeces on the availability of nutrients and their uptake by the crop, and the subsequent plant growth; comparing with the effect of mineral fertilisers, black solider fly larvae composted food waste and cow manure. Semi-structured interviews were carried out and agricultural experts from Ethiopia, Tanzania and Uganda were interviewed to see how farmers and consumers would perceive the use of human faeces as a fertiliser to produce their food, and try to understand the reason to their perceptions. It was found that there is no significant difference in yield if crops are fertilised using either BSF composted human faeces or mineral fertiliser (NPK). Furthermore, it was found that most farmers and consumers would not accept the use of human faeces in agriculture due to various reasons, ranging from personal values, culture, religion, fear of being bewitched, etc. In Uganda, it was highlighted that a few farmers had accepted using their own faeces for food production because of the associated yield increase and the saved cost of buying mineral fertilisers. This study concluded that if accepted by farmers and consumers in sub-Saharan Africa, BSF composted human faeces could be used as a cheap source of plant nutrients, boosting agricultural productivity, evading food insecurity, hunger, undernourishment, and above all poverty reduction.

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Definitions

Food insecurity: exists when people lack adequate physical, social or economic access to safe, sufficient and nutritious food that meets their daily dietary requirements and food preferences for a healthy life (FAO, 2003).

Hunger: is a result of the consumption of food that is persistently incapable of meeting dietary energy needs (FAO, 2003).

Soil nutrient availability: refers to the various chemical forms of essential plant nutrients elements in the soil their chemical state whose variations in quantities are directly responsible for plant development and yield (Bray, 1954).

Conceptual systems: can be defined as the formal or informal rules, norms including conventions that are used by societies to structure relationships (Epstein *et al.*, 2015)

Social-Ecological Systems: are interconnected complex adaptive systems continuously coevolving through the interactions between society, the environment and other numerous coupled systems, all linked together through flows of energy, information and matter (Thiel *et al.*, 2015; Schlueter *et al.*, 2014)

Acronyms

BSF: Black soldier fly
SSA: Sub-Saharan Africa
SES: Social-Ecological System
SESF: Social-Ecological Systems Framework
FAO: Food and Agriculture Organisation of the United Nations
IFDC: International Fertiliser Development Centre
WFP: World Food Program
HEIA: High External Input Agriculture
LEISA: Low External Input Sustainable Agriculture
SE: Systems Engineering
SA: Systems Analysis
S_0: Initial state
S_1: Required state
ANOVA: Analysis of Variance
RS: Resource System
RU: Resource Unit
GS: Governance System
A: Actors

1 Introduction

Chronic food insecurity in Sub-Saharan Africa (SSA) has become an issue of major concern (FAO, 2011; Clover, 2003). An estimated minimum of 25 % of the population suffers from malnutrition (FAO, 2015), and thousands of people die of hunger everyday (WFP, 2016). The issue of food insecurity has become a core manifestation of abject poverty, as poverty increases so does the entrenchment into food insecurity (Cordell *et al.*, 2009; Clover, 2003).

Food insecurity in SSA has been attributed to the fact that 75% of the region's soils are nutrient deficient, mainly due to nutrient mining (Cordell *et al.*, 2009; Michael, 2007). Despite the massive population growth in SSA, agricultural productivity in the region has been stagnant or even declined in some years, and this has resulted in food insecurity, hunger and malnutrition of many people (WFP, 2016; FAO, 2011). The total agricultural production of crops like cereals, tubers and other vital crops did not increase from 1996 to 2006 and in some cases is thought to have decreased (Henao & Baanante, 2006).

Currently, some methods to replenish soil nutrients are being used, including crop rotation, application of animal manure and mineral fertilisers. However, these methods have not been sufficient to address the issue of soil nutrient depletion. Although crop rotation with legumes may help with nitrogen availability, it may require a lot of other nutrients from a supplementary source. For those with animals, access to adequate quantities of animal manure is limited due to low animal stock densities and the fact that most of the animals are free range, making it hard to collect their manure. Cordell *et al.* (2009) and Michael (2007), have indicated that mineral fertilisers are extremely expensive is SSA and farmers cannot afford to buy them.

The inadequacy of the fertiliser systems used in SSA to meet the required agricultural productivity in the region, calls for a different approach that might actually address the issue of soil fertility. A potential solution could be the recirculation of nutrients contained in human faeces back to the fields. In this thesis, the potential of using human faeces to address the problem of nutrient depletion in SSA is investigated.

2 Background

Sub Saharan Africa is a region located south of the Sahara desert and comprises 48 countries within the continent (Fig. 1) and six located on islands. The regional population is around one billion with projections of 2.3 billion people by the year 2050 (Boyes, 2013; PRB, 2013). The climate in SSA

varies from hot desert to tropical climate (Peel *et al.*, 2007), and 65-70 % of the population in the region depends on rain fed agriculture for survival (WorldBank, 2013; Cooper *et al.*, 2008).
Agriculture is not merely a way of producing food and fibre as many modern societies view it today, in Africa it is still a practice deeply embedded in the people's lives. For many centuries, farmers in SSA practiced shifting cultivation in their agricultural "*culture"* to manage soil nutrients, and they had never had to use any form of fertiliser (Pingali *et al.*, 1987).

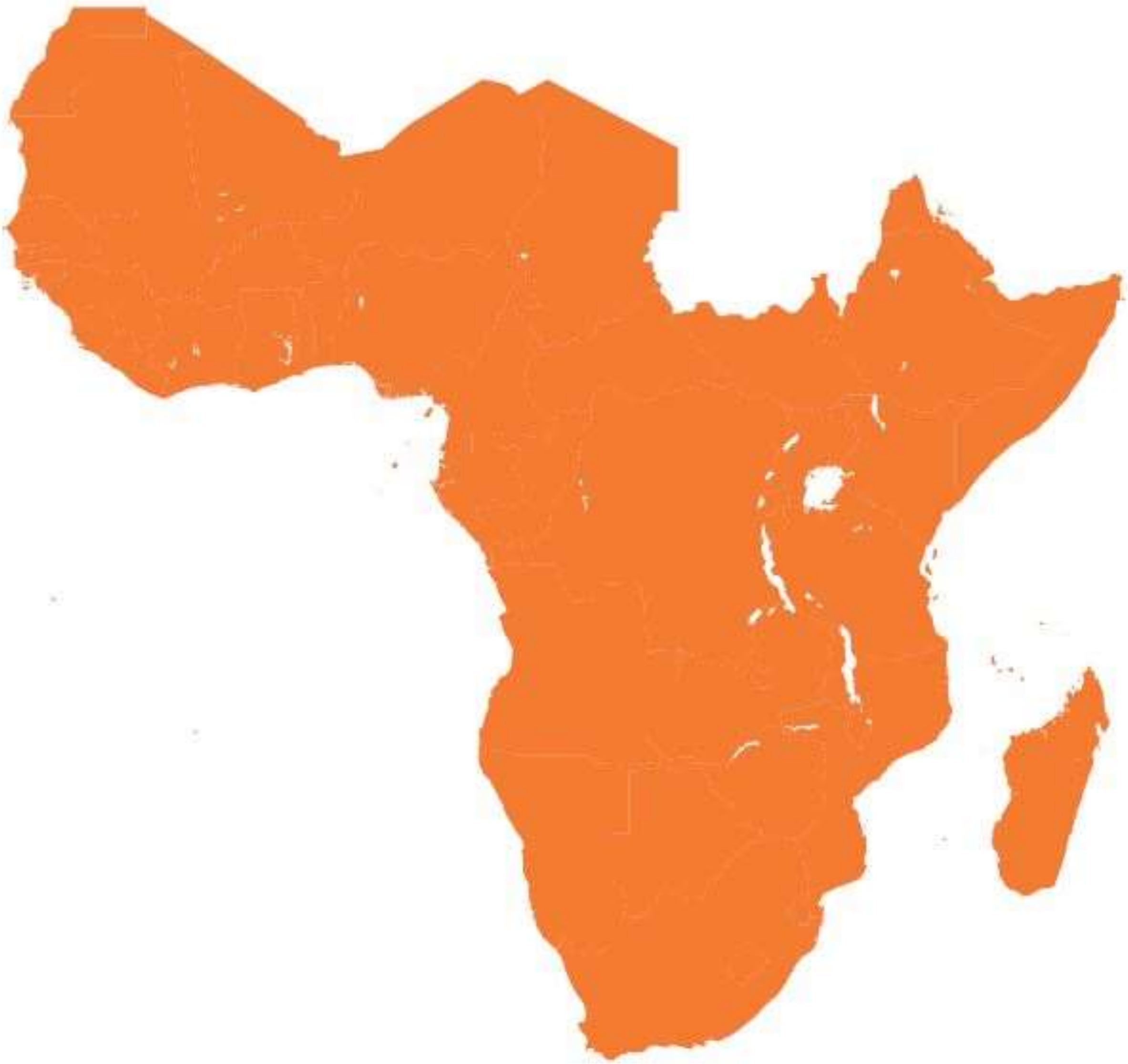

Figure 1.Map of Sub-Saharan Africa. *Source:(FAO & ITPS, 2015)*

The only practice that they were adapted to was of leaving cultivated land for fallowing so that it could naturally regenerate its fertility (Pingali *et al.*, 1987). This cultural aspect of agriculture persisted with time albeit the population increased, resulting in shorter and shorter fallowing periods as more land being occupied by people; causing excessive nutrient mining limiting agricultural productivity in the region today (Heerink, 2005).

Nutrient mining is the net exportation – or net loss of nutrients, known as *depletion* – from the field through crop harvests (Drechsel *et al.*, 2001). It results when the total nutrients added to the soil are less than those extracted from it (Henao & Baanante, 2006). The mining of soil nutrients in SSA is a huge problem that results in reduced agricultural productivity and poverty (Henao & Baanante, 2006). If nutrient mining continues unabated, then food insecurity will be aggravated leading to further entrenchment into poverty (Henao & Baanante, 2006). The problems associated with nutrient depletion are multi-faceted; social and political instability are inevitable consequences in such situations (Clover, 2003). Soil nutrient mining is undermining the survival and welfare of at least 70% of the population in SSA who solely depend on agricultural production (Henao & Baanante, 2006; Clover, 2003).

2.1 Current measures to evade nutrient depletion

In order to avert food insecurity caused by nutrient deficient soils, most farmers in SSA have resorted to cultivating marginal lands and in some cases protected lands (Henao & Baanante, 2006; Drechsel *et al.*, 2001). Farmers use animal manure, household wastes, mineral fertilisers and crop residues to try to replenish soil nutrients for better crop yields (Michael, 2007; Stoorvogel *et al.*, 1993). Sewage sludge is also used by some farmers as a fertiliser, however, it is not very common (Cofie *et al.*, 2005). Crop rotation, alternating cereals with nitrogen fixing plants like cow pea and ground nut is now being used by farmers in some parts of Africa, to improve the availability of soil nitrogen (Sanginga, 2003; Sanchez, 2002).

However, all these measures being used to try to address the issue of food insecurity fall short of their desired goals for various reasons. The marginal lands that are put under cultivation are not fertile enough to sustain the required production, and they simply degrade as soon as they are touched (Henao & Baanante, 2006). The use of animal manure is a challenge because the number of animals owned by most farmers is too small to provide sufficient quantities of manure (Clay *et al.*, 2002; Mekuria & Waddington, 2002). Some farmers do not have any animals, making the prospect of using animal manure impossible (Clay *et al.*, 2002; Mekuria & Waddington, 2002). Crop residues are rarely incorporated into the soil to provide nutrients due to their importance for other utilities such as fuel, animal fodder and as construction material (Pender & Mertz, 2006). The use of mineral fertilisers has been extremely low due to their unaffordability (Vanlauwe & Giller, 2006). The use of nitrogen fixing crops in crop rotation systems has not been enough as nitrogen fixing crops do not fix other essential nutrients that are required for plant growth. Sewage sludge is not attractive to the majority of farmers and consumers due to fear of contracting diseases, hence it has not been widely adopted (Windberg *et al.*, 2005).

2.2 Proposed solutions and their challenges

The issue of soil fertility is subject to fierce debate. There are two main paradigms on how to enhance soil fertility in SSA (Refsgaard *et al.*, 2006) that are highly polarised, and push for different approaches:

1. High external input agriculture;
2. Low external input sustainable agriculture.

2.2.1 High External Input Agriculture (HEIA)

Proponents for high external input agriculture (HEIA), amongst them the World Bank[1], emphasise that only mineral fertilisers can ensure food security for African farmers (IFDC, 2014; Pender & Mertz, 2006). They also argue against organic farming saying that it requires more land area per unit of production as compared to conventional farming, leading to environmental degradation as more marginal lands are cleared for production (Beegle *et al.*, 2016; Liverpool-Tasie *et al.*, 2015).

2.2.1.1 Advantages and disadvantages of using mineral fertilisers

The use of mineral fertilisers is one of the major factors that have played a magnificent role in increasing global agricultural production and has been credited for saving millions of people from starvation and undernourishment (Bindraban *et al.*, 2015; Hazell, 2002). Mineral fertilisers have been proven to increase crop yields, and increase food security beyond any reasonable doubt (Bindraban *et al.*, 2015). In developed farming systems where fertiliser application is done with the help of GIS[2], they can be applied with economic efficiency, and nutrient overload is avoided (Papadopoulos *et al.*, 2015; Nishiguchi & Yamagata, 2009). Another attractive characteristic of mineral fertilisers is that they are concentrated, meaning that the volumes applied per unit area are neither cumbersome to transport nor handle. With some current technological advancements in the fertiliser industries like slow and controlled-release and nitrification inhibitors, nutrients can be released in a manner that they meet plant nutrient requirements throughout the growth period (Trenkel, 1997). This also reduces the risks of nutrient losses through leaching and volatilisation (Trenkel, 1997).

However, there are some disadvantages with regards to mineral fertilisers, in a sub-Saharan Africa context; these fertilisers are extremely expensive for farmers (Cordell *et al.*, 2009; Vanlauwe & Giller, 2006). This is evident from the very low mineral fertiliser application rates in the region which average about 8 kilograms per hectare (Michael, 2007). The changing of diet to more livestock products in most parts of the developing world is likely to push the demand and prices of fertilisers even higher. The rising cultivation of energy crops is also putting further demand for mineral fertilisers (Cordell *et al.*, 2009), could result in higher fertiliser prices. The manufacture of phosphorus fertilisers is dependent on a finite natural resource, phosphate rock and although the peak period is debated to come with 30-40 years by some, others claimed the reserves will last for another 400 years (Ferro *et al.*, 2015), the quality of the remaining phosphate rock and the extraction methods required are unclear (Cordell *et al.*, 2009; Jensen *et al.*, 2005; Driver *et al.*, 1999). Manufacturing of the nitrogen fertiliser - the other main macro nutrient required for plant growth - commonly sold in SSA is highly energy intensive (Roy, 2015; Brentrup & Palliere, 2008)

[1] World WorldBank (2013)
[2]Geographic Information System

and depends on oil, another finite natural resource with its highly disputed peak period estimated around the years 2025-2030 (Robert & Lennert, 2010; Greene *et al.*, 2006). Both the peak phosphorus and peak oil periods will likely be marked by higher prices of fertilisers meaning that they will even be more expensive and inaccessible to SSA farmers.

Most mineral fertilisers do not contain many micro-nutrients, and the application of mineral fertilisers to soils is even thought by some to have exacerbated soil deterioration in SSA (Bindraban *et al.*, 2015; Roy, 2015). Phosphate based fertilisers contain trace elements such as cadmium, lead and uranium and as the quality of mined phosphate decreases the concentrations of these continuously increase in the fertiliser (Kratz *et al.*, 2016; Wang *et al.*, 2016). These toxic elements make the use of such fertilisers unattractive. Production and transportation of mineral fertilisers contributes to greenhouse gas emissions, such as carbon dioxide and nitrous oxide (Robert & Lennert, 2010; Greene *et al.*, 2006), with regards to climate change which mostly affects the world's poor, their use should be minimised (Flynn & Smith, 2010). The use of mineral fertilisers can also result in environmental disasters due to leaching, for example they contributed to the Baltic Sea pollution (Skowronska *et al.*, 2009; Rheinheimer, 1998).

2.2.2 Low External Input Sustainable Agriculture (LEISA)

Antagonistic to the HEIA approach is the low external input sustainable agriculture (LEISA) which emphasises the importance of closing the nutrient cycle by using animal manure, compost application, and incorporation of crop residues among other soil management practices (Pender & Mertz, 2006). The proponents of LEISA, La Via Campesina[3] amongst others argue that conventional agriculture has already failed in Africa, and that organic farming has considerable potential to improve yields significantly (Pender & Mertz, 2006). Cordell et al. (2009) and Michael (2007) have also indicated the importance of organic fertilisers to improve nutrient availability in Africa's soils.

2.2.2.1 **Advantages and disadvantages of using organic fertilisers**

The use of organic fertilisers in SSA has been recommended for various reasons. They are a very inexpensive source of plant nutrients that can be easily procured by farmers (Omotayo & Chukwuka, 2009; Refsgaard *et al.*, 2006). Organic fertilisers are available during any time of the year making it easier for farmers to use them whenever needed. One of the biggest advantages of using organic fertilisers over ordinary mineral fertilisers is that they contain both macro and micro nutrients (Roy, 2015; Bindraban *et al.*, 2014). Organic fertilisers also contain a lot of organic matter which is slowly broken down by soil microflora, allowing the slow release of nutrients to plants, even over a period of a number of years (Omotayo & Chukwuka, 2009). Organic matter is also important as it helps improve the physical structure, texture, chemical and biological

[3] An International Peasant's Movement Organisation

composition of the soil, resulting in better water retention capacity (Diacono & Montemurro, 2010; Nardi *et al.*, 2004), which is good for rain-fed agriculture. In urban centres where waste management is poor, the prospect of making organic fertilisers from urban waste might even create incentives for better waste management resulting in cleaner cities (Lalander *et al.*, 2015b).

Accessibility of organic fertilisers in SSA is dependent on the type of fertiliser in question. With regards to animal manure, many domestic animals in SSA are free range, which makes it difficult to collect their dung for agricultural purposes. Another challenge is that animal dung serves other important roles in the household, for example cattle dung is combusted to produce energy for cooking, especially in highly deforested areas. Recycling urban organic waste from cities back to rural farms where it is mostly needed is very difficult due to limited access to affordable transportation systems (Refsgaard *et al.*, 2006). The voluminous nature of most organic waste makes it difficult to carry, handle, and spread on the fields. For example in Uganda, urban and peri-urban farmers rejected vermicomposted fertiliser because of its bulkiness and low nutrient concentration (Komakechi, 2016). The use of organic waste, especially of human and animal origin, as fertilisers can also present health challenges as pathogens and other communicable diseases might easily spread if it is not handled adequately (Refsgaard *et al.*, 2006). In case of sewage sludge, it may contain organic pollutants and toxic industrial residues which might affect human beings adversely if consumed through contaminated plants (Refsgaard *et al.*, 2006).

2.2.3 Use of human excreta in a global context

The use of human excreta is an old tradition that dates centuries back. Even though it has been abandoned in Europe, Asia has continued the use of human excreta to present day (Jensen *et al.*, 2005). China and Vietnam are well known practitioners of this tradition (Jensen *et al.*, 2005). However, in both countries a considerable percentage of the population is known to be infected by intestinal parasites like *Ascaris lumbiricoides* due to the use of poorly sanitised excreta (Verle *et al.*, 2003; Peng *et al.*, 2002). The Vietnamese government has tried to legislate the use of excreta in agriculture to control pathogens, but the efforts have been fruitless since farmers do not respect the recommended composting time (Jensen *et al.*, 2005). Jensen *et al.* (2005), highlighted that in China and Vietnam farmers are so much attracted to the use of human excreta which is a mixture of urine and faeces because of its benefits:

i. It is a cheap source of agriculture nutrients and there is no need to purchase chemical fertilisers;
ii. It is a good soil amendment;
iii. It is a very important way for recycling nutrients back to the field.

2.2.4 Use of human excreta in a sub-Saharan Africa context

There is no conclusive evidence for the use of human excreta in sub-Saharan Africa agriculture. In Zimbabwe, urban dwellers grow maize and vegetables using sewage water after the solids have been removed at the treatment plant. In other African countries only the urine part of human excreta is used as fertiliser (Dunker *et al.*, 2007). Faecal matter has been collected in various African countries for use in silviculture[4] (Dunker *et al.*, 2007). Concrete evidence for the direct use of human excreta in agriculture is only from experiments carried out by researchers in collaboration with certain rural communities (Dunker *et al.*, 2007; Guzha, 2004). For example, ecological sanitation demonstrations gardens have been established in some districts of Uganda and various food crops have been grown and harvested (Dunker *et al.*, 2007). However, it is difficult to find evidence of the continued use of human excreta after the closure of the demonstration garden projects. Windberg *et al.* (2005) attributed these projects failures to the people's unwillingness to accept the use of human excreta on their farms.

In exceptional cases where human excreta is widely used to grow food, it is through planting trees or vegetables on top of disused pit-latrines (Dunker *et al.*, 2007). Another exceptional case is in one district in northern Ghana where people used to put faecal sludge on their fields, left it to dry, and later spread it. However, farmers ended up suffering from itchy feet and foot rot, leading to demotivation towards the use of the sludge (Cofie *et al.*, 2005). Of course, the faecal sludge that was used by farmers in Ghana is said to have been disinfected by prolonged drying, but the measures were not good enough to completely sanitise the faecal material (Cofie *et al.*, 2005). In Nigeria (and probably other countries), excreta has been "used" in the agricultural systems. "Used" in the sense that the lack of sanitation facilities in many African countries (WHO, 2015) has led to the indiscriminate defecation on fields and behind every bush available (Cofie *et al.*, 2005).

2.3 Solving the challenges of using human faeces using black soldier fly larvae

Although there are many challenges regarding the use of organic fertilisers, their benefits are quite numerous. There is a very important technic which could tackle the current challenges, but it has not yet been widely explored. It is the use of black soldier fly (BSF) larvae to compost organic and faecal waste. The use of BSF larvae for composting is an innovative way of converting organic waste into two valuable products: organic fertiliser, as treatment residue; and animal feed protein, as larvae (Lalander *et al.*, 2015a). The two products of BSF larvae composting can be sold, this makes organic waste management lucrative, and opens up for the possibility of the treatment to bears its own cost (Diener *et al.*, 2011). Black soldier fly larvae can be used to compost human faeces by simply adding the young larvae to a fresh mass of faeces on which they can feed. The treatment residue (the frass) is collected as organic fertiliser, while the larvae become animal feed. Black soldier fly larvae can reduce the wet weight of faecal material by up to 83 % (Dortmans, 2015). A total reduction of 73% dry weight of faecal material has been demonstrated using BSF larvae (Lalander *et al.*, 2013). The significant reduction in weight makes the possibility of commercial onsite treatment of faecal material attractive as the prospective transportation costs of faeces will be heavily reduced (Diener *et al.*, 2015). The concentration of phosphorus (mg/g) in the post-treatment faecal residue was found to be significantly higher than in untreated material.

[4] Silviculture is the growing and cultivation of trees.

This makes BSF larvae invaluable in the weight conversion of faecal material (Lalander *et al.*, 2015a). However there was no statistically significant change in nitrogen concentration in the faecal residue after composting, even though the nitrogen concentration had reduced (Lalander *et al.*, 2015a).

Black soldier fly composted faeces can be used in agriculture if all necessary procedures are adequately followed. The concentration of zoonotic bacteria and viruses in faeces has been shown to significantly decrease to acceptable levels following composting using BSF larvae (Lalander *et al.*, 2013). However, in areas prevalent to *Ascaris lumbricoides,* or other parasites, BSF composting may not be sufficient for the safe utilisation of excreta in agriculture and further treatment would be required, for example ammonia sanitisation has been suggested (Lalander *et al.*, 2013). In tropical and sub-tropical areas where temperatures are usually high, the heat could be used to help increase the temperature in the faecal residue to above 55° C, the temperature which is required for sanitisation. Sunlight drying has also been suggested to improve the sanitisation of the larvae before use as animal feed (Lalander *et al.*, 2013).

2.4 Aims

The aim of this study was to investigate the potential of using BSF composted human faeces as a fertiliser for use by smallholder farmers in sub-Saharan Africa.

Research questions

Can black soldier fly larvae composted human faeces be used by smallholder farmers in SSA to replenish soil nutrients as a sustainable solution to the problem of soil nutrient depletion in the region?

To answer this question, the following questions were developed:

1. What is the effect of BSF composted human faeces on the availability of nutrients in soil and their uptake by plants, and the subsequent plant growth in comparison to mineral fertilisers, food waste compost and cow manure?
2. How would farmers and consumers perceive the use of human faeces as a fertiliser to produce their food, and why would they have this perception?

3 Theoretical Framework

3.1 Agroecology

Due to spatial variation, the field of agroecology is widely diverse in its approaches and definitions. In one place it is seen as a scientific discipline, in another as a movement, whilst in others as a practice (Wezel *et al.*, 2009). Agroecology has been defined as *"the integrative study of entire food systems, encompassing ecological, economic and social dimensions"* (Francis *et al.*, 2003). Gliessman (1998) defines agroecology as "*the application of ecological concepts and principles to the design and management of sustainable agroecosystems".* Agroecology is the responsible stewardship of the environment and the agroecosystem while practicing sustainable farming methods that enhance future agricultural production capacity.

Agroecology tackles agricultural issues by studying: production systems at farm level; the supply chain; the economic and political factors involved; consumer behavior; and how all these reflect on the environment (Wezel *et al.*, 2009). It also promotes a moral obligation by seeking equity for all people with regards to nutrition, health, and food security (Francis *et al.*, 2003).

The definition of agroecology given by Gliessman (1998) above, suggests that innovative ways can be used to increase productivity and sustainability of agricultural systems simultaneously maintaining a durable environment.

3.2 Social Ecological Systems Framework

In this thesis, some (system) mechanisms that could help close the nutrient cycle are being explored in an attempt to meet the moral obligation of ensuring food security for people in SSA. From an agroecological perspective, this exploration is appealing as it assists focusing on the structures and processes that are required at each relevant system level in order to implement the desired solutions. Agriculture is an open system in which there is constant interaction between the natural and social systems (Francis *et al.*, 2003). The sustainable development of such a system requires paying particular attention to the efficiency of the whole process, from using natural resources in the field until food consumption (Francis *et al.*, 2003). To address issues of a complex system as agriculture, a tool that acknowledges the equal importance of both nature and society is required; the Social Ecological Systems Framework (SESF) is such a tool.

An essential part of dealing with complexity of managed resource systems is the acknowledgement of the intense and complex coupling between social and ecological systems (Ostrom, 2011). The SESF is an integrative framework (Bots *et al.*, 2015) that renders a holistic approach to diagnosing and analysing challenges and probable solutions to complex social-ecological systems (Liu *et al.*, 2007; Berkes & Folke, 1998). The diagnostic and analytical capacity depends on the framework's ability to identify a range of functional variables and crucial relationships among the variables that are essential for consideration when studying cross disciplinary concepts (Hertz & Schluter, 2015; Thiel *et al.*, 2015; McGinnis & Ostrom, 2014). The SESF was built on various interdisciplinary frameworks stemming from complex systems thinking. Hence, the framework comprises social context, multi-disciplinarity, holistic thinking, and other approaches that enhance adaptation (Armitage *et al.*, 2009). For example, the framework has been successfully used to address the management of forests, fisheries, rangelands and other natural resources (Bots *et al.*, 2015; Hertz & Schluter, 2015; Leslie *et al.*, 2015; Liu *et al.*, 2007).

The SESF was selected because it is a general framework that is theory-free. Theory-free means that the framework does not rely on a specific theory, but rather encompasses many theories from different disciplines (Thiel *et al.*, 2015). This enables relevant variables and processes influencing human behaviour and decision making often found in various theories and models, to be represented and organised within the framework (Schlueter *et al.*, 2014; Feola & Binder, 2010). It is one of the few comprehensive frameworks that avoid the problem of disciplinary approaches that may horrendously simplify the ecological or social dimensions of a problem. This simplification of the ecological or social dimensions of a problem results in explorative short falls towards explaining feedbacks that drive complex and coupled social-ecological systems (Schlueter *et al.*, 2012).

Social-Ecological Systems are interconnected complex adaptive systems continuously coevolving through the interactions between society, the environment and numerous other coupled systems all linked together through flows of energy, information and matter (Thiel *et al.*, 2015; Schlueter *et al.*, 2014). The interactions that exist within social-ecological systems can be unidirectional or bidirectional and they are not always linear, which makes it difficult to explain some of the dynamics which take place in such systems (Hill *et al.*, 2015; Ostrom, 2009). Social-ecological systems are nested within bigger systems, which they also interact with (Ostrom, 2009). This is the case with agriculture, a social-ecological system that influences and is influenced by other social ecological systems. Social Ecological Systems are composed of Actors, Governance Systems, Resource Systems and Resource Units (Leslie *et al.*, 2015; Schlueter *et al.*, 2014).

3.2.1 Application of the Social-Ecological Systems Framework to this study

In this thesis the framework totally depicts the inseparable nature between humans (society) and the soil. A healthy and fertile agricultural soil requires human management (society), in-turn a healthy society depends on the productivity of a healthy and fertile agricultural soil (FAO & ITPS, 2015). The Social-Ecological Systems Framework can be split into two *separate*[5] systems/parts of a whole: the ecological system and the social system.

Ecological system

The ecological system is made up of two components: the resource units (RU) and the resource system (RS). The resource units are plant nutrients, and they are in turn part of the resource system. The resource system is the soil, including all the various dynamic relations of its components (plant nutrients, microflora, pedo-fauna, organic matter, etc.).

Social system

The social system is made up of the governance system and actors. The behaviour of actors, whether involved with consumption or production, affects the dynamics that could take place in an agricultural system. This behaviour exhibited by actors is influenced and/or driven by the governance systems, which control and/or regulate their actions. These governance systems are created, or rather constructed, by actors. However, it is also important to acknowledge that the social system as a whole influences, and is influenced, by other external Social, Economic, and Political Settings (S), all comprising within a larger society. The previous sentence gives the

[5] They are not separate in real sense but in this case they have been unharnessed in order to study them.

impression that the external Social, Economic, and Political Settings (S) do not affect the ecological system; however, they do. They affect land rights, enforce legislation on conservation etc., but they were beyond the immediate concerns of this thesis in those respects. Other external Related Ecosystems (ECO) are affected and affect the social-ecological system under analysis in this study, but focus will be put on how they affect the social system only.

The interactions (I) within and between social and ecological systems are complex and non-linear but some of them can be "*simplified*" to show a comprehensible picture (Fig. 2). The interactions within the demarcated social-ecological systems affect, and are affected, by other social and ecological factors external to the system.

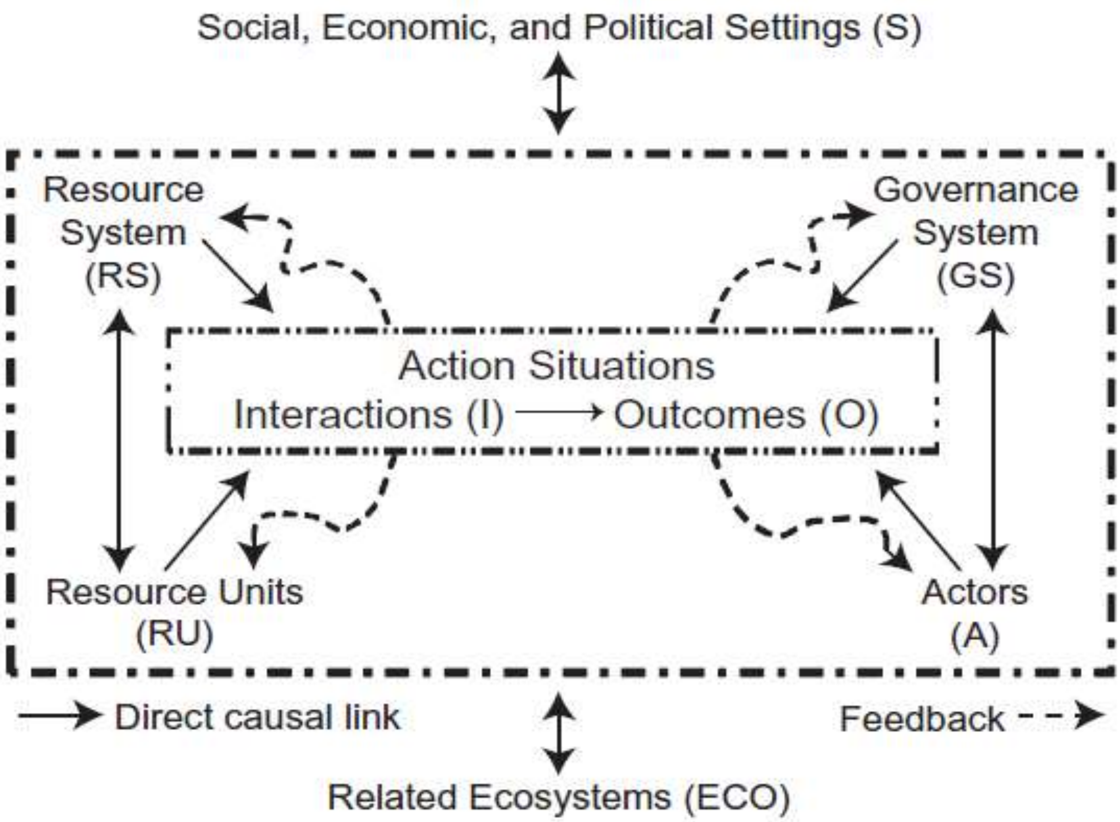

Figure 2. The Social-Ecological Systems Framework, illustrating the various interrelationships that take place within and between social and ecological systems. *Source: (Ostrom, 2007).*

Solving the issue of nutrient depletion requires action at an ecological level so that there is an available solution for the betterment of social welfare for those affected by the ecological problem. The Social Ecological Systems Framework is hence used to:

1. Investigate and evaluate the relevant actions that need to be taken at the ecological system level to try to solve the problem of nutrient depletion sustainably. This also encompasses

examination of the various components that exist in the ecological system and how they relate with each other within.

2. To diagnose and analyse the social concerns of the people to whom the ecological solution is being recommended. This helps identify the factors that might drive or hinder acceptance of the recommended solution.

3.3 Methodological Approach

In this thesis, methods from natural sciences are used to evaluate the effect the addition of nutrients to the ecological system (soil) has on plant growth and whether the source of nutrients impacts this effect. Social sciences methods are used to integrate the human aspects related with the enhancement of the ecological system (soil) in order to have a better understanding of the whole agricultural system (Francis *et al.*, 2003). An agricultural system is embedded in deep political, economic, cultural (social) and at times religious controversies (Eckholm, 1978), to understand it holistically, there is need for the employment of holistic or systemic thinking.

Systems thinking

Systems thinking take a holistic approach to the analysis of systems. It recognises that systems are made up of components and interrelationships amongst these components. Systems thinking also acknowledges the interactions that may exist between, or among different systems, to form a larger system (Checkland, 1993). Systems thinking can be split into two: hard and soft systems thinking. With reference to the Social-Ecological Systems Framework, the hard systems thinking was used to address issues related to the ecological system by employing empirical quantitative[6] methods. Soft systems thinking was used to address issues related to the social system, using qualitative[7] methods. These two ways of thinking can be regarded as methodologies when they are applied to solve issues; the hard and soft systems methodologies (Checkland, 1993).

3.3.1 Hard Systems Methodology

Hard Systems Methodology is a combination of two systemic approaches: Systems Engineering (SE) and Systems Analysis (SA) (Checkland, 1993). The two approaches are based on the same idea that a certain class of real-world problems can be formulated in terms of the required state S_1 and that of the current state S_0, and that there are a number of ways of transitioning from S_0 to S_1 (Checkland, 1993). This approach to problem solving consists of first defining both S_0 and S_1 and selecting the most lucrative measures of reducing the difference between S_1 and S_0 (Checkland, 1993).

"Thus in SE (S_1-S_0) defines 'the need', or the objective to be obtained, and SA provides an ordered way of selecting the best among the alternative systems which could fulfil that need."
(Checkland, 1993)

[6] Natural science
[7] Social science

In this thesis the problem has already been defined; it is soil nutrient depletion in SSA that is of concern. It is already known, ***'what?'*** needs to be done to move from the current state S_0 of nutrient depletion to the crucially desired state S_1 of nutrient replenishment. The question is, ***'how?'*** to solve it, given the aforementioned complex challenges (Section 2.2). In this case, hard systems thinking was used in the thesis to facilitate decision making in choosing the most efficient, ecologically and economically feasible approach (Checkland, 2000) to reach the desired state S_1.

The transformation from S_0 to S_1 is simply a technical solution to solving the ecological problem faced by smallholder farmers in SSA. However, it falls short of recognising the importance of the sociological, ethical and spiritual implications it has on the people it is meant to serve (Bawden, 1991; Carol *et al.*, 1988). This calls for a complementary approach, Soft Systems Methodology, which looks into the associated social dynamics that may arise as a result of trying to implement such a technological solution for addressing an ecological problem.

3.3.2 Soft Systems Methodology

Soft Systems Methodology attempts to unveil various and sometimes diverging or conflicting stakeholders' perspectives and to show that the different ways of viewing a problem situation may have equal rationality (Ison *et al.*, 1997). Given the complexity and the varying perceptions of the 'problem metaphor' (Lakoff & Johnson, 1980), it is extremely important for the 'actors' to formulate the 'problem' as a first step to the problem solving process (Ison *et al.*, 1997). This has been defined as a creative process where problem formulation is important, before any attempt is made of solving the problem itself (Burgess, 1979).

In this thesis, soft systems methodologies were applied to the social system component of the social-ecological system. It was used to identify the invisible various institutions (governance systems) or social structural variables and other factors that determine or structure actors' patterns of interactions (behaviour). In this case there is a 'problem metaphor', that is, the use of human faeces in agriculture, which may be subject to varying and probably diverging perceptions amongst actors. According to Thiel *et al.* (2015), social structural variables have a contingent causal connection to perceptions. However, the resulting perceptions are based on actors' evaluation(s) of trade-offs in the "perceived costs and benefits" (Ostrom, 2011), associated with a particular action. These perceived costs and benefits act as incentives, or deterrents, towards that action (Ostrom, 2011). In this thesis, the "perceived costs and benefits" of using human faeces in agriculture was evaluated by actors against their various social structural variables for them to decide whether to accept or reject using faeces in their agricultural systems.

Social cultural variables will be interchangeably referred to as Institutions or conceptual systems; and these can be defined as the formal or informal rules, *norms*, including conventions that are used by societies to structure relationships (Epstein *et al.*, 2015).

3.4 Materials and methods

3.4.1 Pot Trials

Experimental setup

A completely randomised block design experiment was performed. Five treatments were included: black soldier fly composted human faeces (FC) and food waste (FWC); the commonly used fertilisers, cow manure (CM) and mineral fertiliser (NPK) were positive controls; and soil (C) was a negative control. There were three blocks with four replicates per treatment.

Calculation of fertiliser quantity

The quantities of fertiliser to be added to each pot (F_{pot}) were based on a selected limit of 100 kg per hectare of readily available nitrogen (N) and were calculated from the amount of fertiliser applied per hectare (F_{ha}):

$$F_{ha} = \frac{N_{ha}}{N_{tonne}} \qquad (Equation\ 1)$$

Where, N_{ha} was the amount of nitrogen allowed per hectare and N_{tonne} was the available nitrogen in one tonne of fertiliser. Thus, F_{pot} added in grams was calculated as:

$$F_{pot} = \left(\frac{A_{pot} \times N_{ha}}{A_{ha}}\right) \times 1000 \qquad (Equation\ 2)$$

Where, A_{pot} was the area of the pot used (in m) and A_{ha} the area of one hectare (in m^2).

Equation 1 and 2 were used to calculate the amount of fertiliser added to each pot (Table 1).

Table 1. Amount of nitrogen to be available for plant uptake during the growth period and the amount of each fertiliser added per pot.

	Fertiliser			
	NPK	FWC	FC	CM
Total N (%)	11	3	3	2
Readily available N as % of total N	100	10	10	10
N available after mineralisation as % of total N	-	30	30	30
Total N available during growth period as % of total N	100	40	40	40
Amount of fertiliser that could be added to have 100 kg N/ha (kg)	909.1	8333	8333	12500
Amount of fertiliser added per pot basing on pot area (g)	1.6	14.7	14.7	22.01

Plant rearing

Pot trials to determine the effect of FWC and FC in comparison with CM (Weibulls Horto AB, Hammenhog, Sweden) and NPK (Svenska Foder AB, Lidkoping, Sweden) on plant nutrient uptake, availability and plant growth were carried out in a greenhouse at the Swedish University of Agricultural Sciences, Alnarp, Sweden. Soil (Weibulls Horto AB, Hammenhog, Sweden) with a very low nutrient content was used as a control (C). Swiss chard (*Beta vulgaris*) (Olssons Frö AB, Helsingborg, Sweden), a leaf vegetable was used as a common crop. The faecal and food waste composts used were composted using black soldier fly (*Hermetia illucens*) larvae and were supplied by the Swedish University of Agricultural Sciences, Uppsala, Sweden. The composts were not sterilised. The duration of the experiment was five weeks. Greenhouse conditions were set at a temperature of 20°C, relative humidity was 70% and natural light was supplemented using sodium lamps for a period of 16 hours a day.

The crops were cultivated in 1.5 l pots and tap water was used for irrigation. Upon germination, multiple shoots emerged from the same seed, and they were removed by hand on the 11th day after sowing, discarded, leaving only a single shoot per pot. Development of new leaves on each replicate was noted and recorded according to the dates on which they were first noted. Plant height was also measured on a weekly basis starting from the 11th day after sowing.

3.4.1.1 **Analyses**

Plant growth parameters

Plant biomass in the form of fresh and dry weight was determined at harvest. The shoots were oven dried for 96 hours at 70 °C. Throughout the duration of the experiment plant height was recorded.

Nutrient Content Analyses

Nutrient content in leaves and in the soil was determined at harvest. Sap analysis was done for the leaves whilst the Spurway method was used for soil analysis. All analyses were done at LMI laboratories, Helsingborg, Sweden for analyses. All values are means calculated from four replicates

Microbial Analysis

For microbial analyses 1 g of soil from each treatment was placed in 15 ml tubes and mixed with detergent solution (0.1% peptone and 0.2% sodium hexametaphosphate) for the separation of the microflora from the soil according to Khalil *et al.* (2009). The tubes were placed on a shaker for 20 min. Thereafter, 1 ml of the suspension from each tube was subjected to a dilution series in order to determine the bacterial and fungal concentrations in the different treatments. Tryptic soy agar (TSA) was used for enumeration of bacterial flora and the plates were incubated at 37 °C for two days. Malt extract agar (MA) was used for enumeration of fungal flora and the plates were incubated in 18 ^{o}C for five days.

Statistical Analyses

General linear model, one-way analysis of variance (ANOVA) with 95% confidence interval was used for the data analysis and equal variances were assumed. Statistical significant difference in the means of different treatments was determined using the Tukey method with confidence 95% confidence interval ($p<0.05$). The standard error (SE) was calculated by dividing the standard deviation of the sample by the square root of the number of samples.

3.4.2 Interviews

3.4.2.1 **Method**

The purpose of this part of the study was to investigate the various concerns and perceptions held by farmers and consumers (actors) with regards to the use of human excreta in agriculture. The study was also meant to explore the driving forces underlying these perceptions. In order to achieve the purpose of the study, a qualitative approach was used. The specific method used were semi-structured interviews because they are open ended, and they allow an in-depth inquiry into complex social systems.

A total of five interviews were carried out for this study, two of the interviews were face to face, whilst the other three were carried out over the phone. The interviews were conducted during the period from the 1st to the 18th of March 2016. The interview respondents were experts who were actively involved in agriculture related issues in Africa. Respondents were guaranteed anonymity and were fully informed about what the information they provided during the interviews was going to be used for. Permission to record the interviews was requested from the respondents and was granted in all cases.

Semi-structured interviews are based on Participatory Rural Appraisal (Verle *et al.*, 2003) approaches. A participatory approach or collaborative inquiry are methods consistent with systems thinking. They embrace complexity and chaos, enabling sensitive ‘action’ researching systems that enhance the creation of knowledge that leads to understanding of the various reasons underlying stakeholders’ differing perceptions of the problem situation (Bawden, 1991). In PRA approaches, stakeholders’ knowledge and concerns are paramount in formulating the problem (Chambers, 1994; Ison & Ampt, 1992).

English was the language used during all interviews. The interviews were guided by predetermined questions that were based on specific themes. However, the actual questions asked were based on the respondents’ professional backgrounds, but still covering themes of interest. The interview guides were motivated by the SESF, questions focused on the current interrelationships between Social and Ecological components of the *agroecosystems* in SSA. A future scenario using human excreta to transform the Ecological system was postulated and focus was put on the emergent properties (powers) that could affect the Social system dynamics.

Respondents

Only African nationals were selected as interview respondents. This is because the context and scope of the thesis is solely focused on addressing issues of soil fertility in SSA where nutrient depletion has been chronic. However the interviewer is aware of the potential to use human excreta in agriculture in most countries of the world.

A total of five people were interviewed, and they were from Ethiopia, Tanzania and Uganda. Their backgrounds were as follows:

- university professor working with land and water management;
- lecturer working with composting and soil fertility;
- lecturer working with composting, organic agriculture, involved with extension services and consultancy;
- extension services worker, involved with ecological sanitation projects;
- post-doctoral researcher.

The reason why a professor working with land and water management was selected, was to investigate the current patterns and challenges with regards to land use. The lecturer dealing with soil fertility and composting was selected to see what current methods of enhancing soil fertility were being taught in an African university. The lecturer involved with composting, organic agriculture, extension and consultancy services would help identify the type of organic fertilisers being used in one African country. The respondent would also help identify the current challenges and opportunities with regards to extension and consultancy services in an African context. The extension services worker involved with ecological sanitation projects would help identify the current challenges and probably opportunities associated with using human excreta in agriculture. The post-doctoral researcher was regarded as a consumer, and someone who could give extra information on how people in SSA could perceive the use of human faeces in agriculture. Overall, the respondents were indispensable as they could give an insight of the various perspectives that could exist in their countries with regards to the use of human excreta in agriculture.

Smallholder farmers in SSA could not be interviewed by phone since this would have been cumbersome to organise. Apart from that, most of them do not speak English, this would have meant involving a translator, which may not have been feasible over phone interviews

Data Analysis and Presentation

Semi-structured interviews are used to generate qualitative data. To make sense of the data, causality analysis was used to identify the ‘causal powers’ or ‘liabilities’ (Sayer, 2010) influencing the emergence of powers that could affect social system dynamics. In this case, ‘causal powers’ are reasons, or conceptual systems, that drive acceptance of the use of excreta whilst ‘causal liabilities’ are reasons that hinder acceptance. Analysis of the data started after the very first interview by identifying 'causal powers' or 'liabilities' (causalities). In subsequent interviews, particular attention was put on the (non-)emergence of causalities that had been highlighted in the preceding interview(s). In cases where causalities from previous interviews were not covered in subsequent ones, respondents were asked about these causalities. This was done in a bid to progressively check for similarities and/or differences in the information that respondents shared. At the end of the study, all interviews were summarised and themes were coded according to whether they were 'causal powers' or 'liabilities'. However, some other interesting themes unanticipated by the interviewer were also coded and are discussed in relevant sections.

Quotations from different respondents are included in the results. This is done in order to provide the actual weight of words provided by the interview respondents instead of only the interviewer's interpretation.

Reliability, validity, shortcomings and sources of error

The greatest challenge in this study was the unavailability of both time and financial resources to travel to SSA to interview farmers and consumers. It would have been very helpful to get information from farmers' and consumers' self-reports about their perceptions regarding the use of excreta in agriculture (Lyberg & Kasprzyk, 1991). Unfortunately, only proxy reports subject to the interviewees' cognitive and interpretive capacities were received and this could have introduced some error in the information recorded (Lyberg & Kasprzyk, 1991).

Even though there is a probability that the information provided might have been erroneous, it is still considered credible. Three of the five people interviewed work participatively or collaboratively with farmers. This may have given them empathetic capabilities resulting in them sharing the same perceptions that could have been shared by farmers. The respondents were also native to the social systems investigated in the study, this factor made them likely understand the various structures and relations governing their societies, hence enhancing their capacity to share reliable information. The other reason why the information is deemed valid is that, in cases where respondents were not sure about something, they would simply confess that they did not know.

4 Results

4.1 Hard systems methodology

After analysis of the various approaches that could be used to address the issue of soil nutrient depletion in SSA, BSF composted human faeces was hypothesised by the author to have the desired potential of solving the problem in a sustainable way. There is also literature (Cofie *et al.*, 2005; Guzha *et al.*, 2005; Winblad & Simpson-Hébert, 2004) which suggest that human excreta has the potential to be used as fertiliser. Basing on the hard system methodology analysis and the literature review, the potential of using human excreta in SSA agriculture to tackle the issue of soil nutrient depletion to transition from S_0 to S_1 was selected as interesting for further investigation.

4.2 Pot Trials

4.2.1 Weight

The fresh weight of leaves from FWC was significantly higher than that of CM and C, but it was not significantly different from that of NPK and FC (Fig 4 a). The dry weight of leaves from NPK was significantly different from that of CM and C, however, it was not significantly different from that of FC and FWC (Fig 4 b).

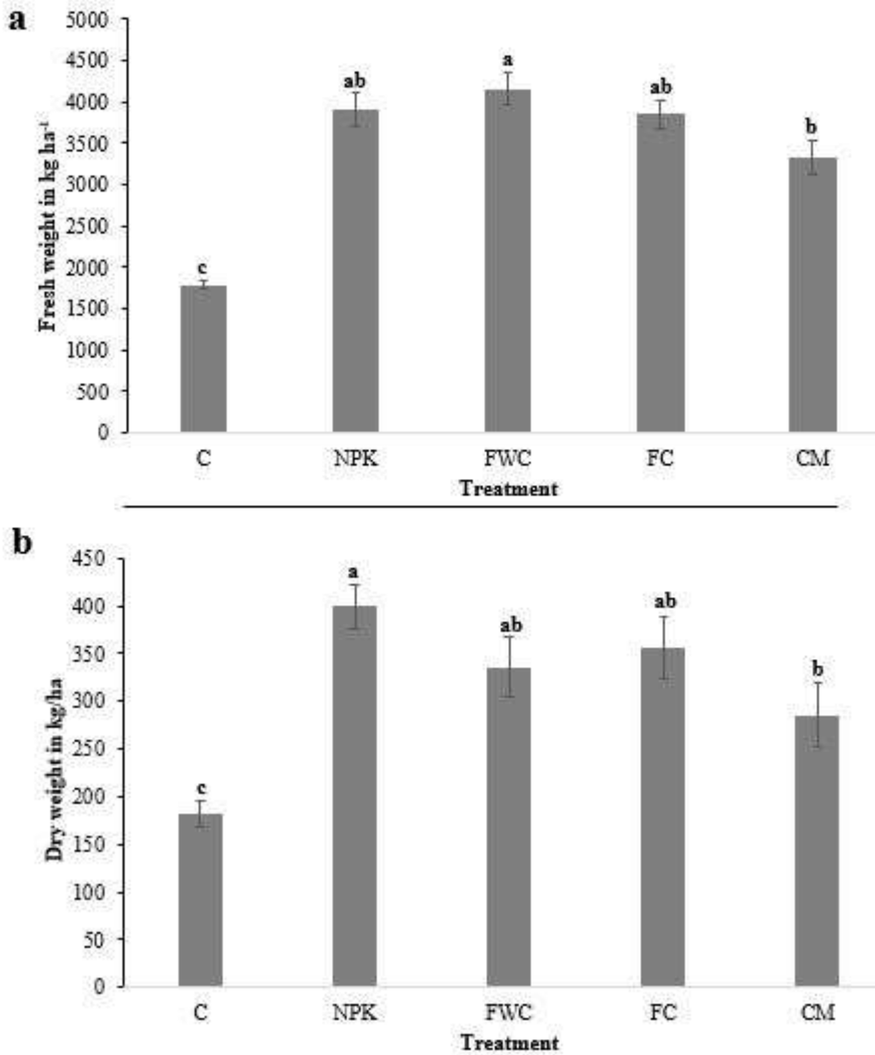

Figure 4. (**a**) Fresh and (**b**) dry weight of Swiss chard plants in kilograms per hectare when grown in different treatments. Different letters on top of each bar show that there is a significant difference ($P<0.05$) between the treatments, whilst the same letters mean that there is no significant difference. Each bar represents a mean (± SE).

4.2.2 Soil nitrate and ammonium content

To investigate the form of nitrogen in the soil that could be available for uptake by plants, the nitrate and ammonium concentrations available in the soil were measured in mg/l. Generally, in all treatments, the form of nitrogen that was available in large quantities for uptake was nitrate. Ammonium was available, but in very small quantities. There were significant reductions in ammonium concentration considering the initial and final quantities that were available in the soil (Fig 5a). Differences in ammonium concentration among the treatments at harvest were not significant, FWC and FC had the highest and equal concentrations, followed by NPK, CM and C in the order of reducing concentrations. As for nitrates, the NPK treatment had significantly the highest concentrations compared with the other treatments (Fig 5 b). There was no significant difference in nitrate concentrations in the other treatments, in descending order FWC had the highest concentration, followed by CM, then FC and lastly C. Initial nitrate concentrations were as low as less than 0.5 mg/l, but final mean concentrations were as high as 6.5 mg/l for FC, 17.25 mg/l for FWC and 11.25 mg/l for CM.

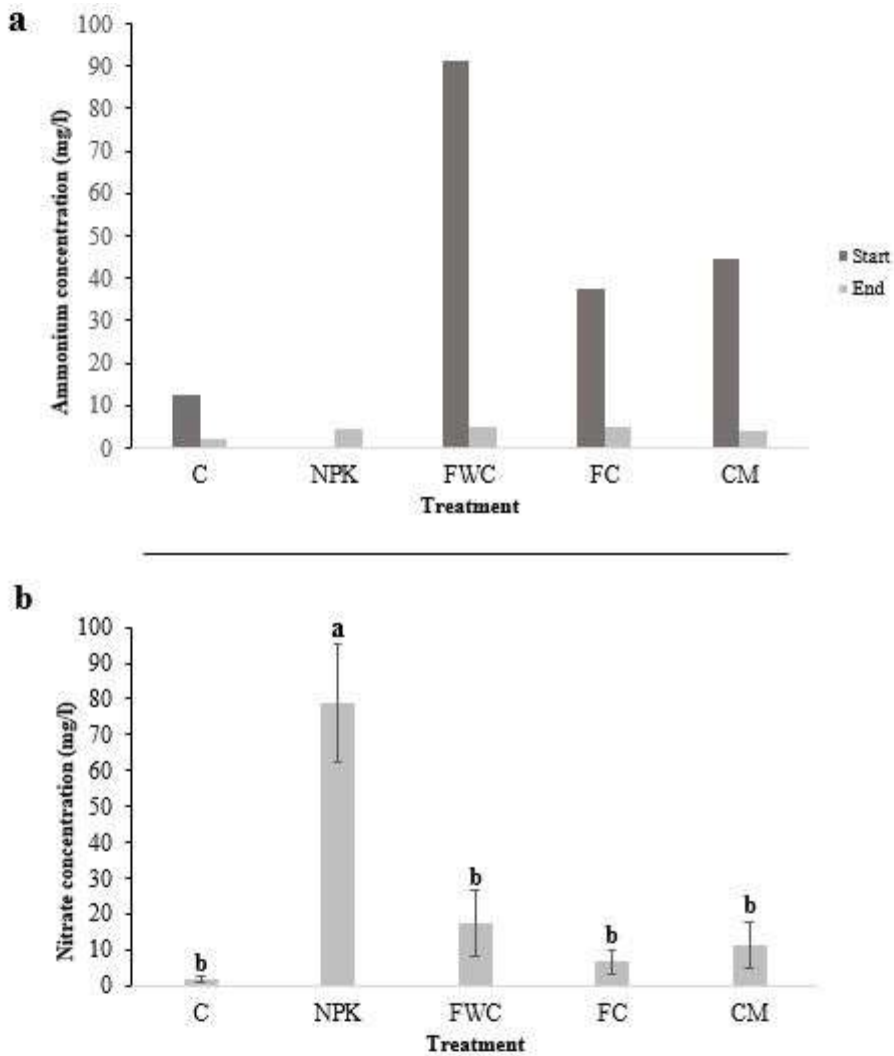

Figure 5. Concentration of available nitrogen in the soil. (**a**) Ammonium concentration at the start and end of the experiment. For the treatments with fertiliser, the amount of ammonium already present in the soil is not considered in the figures. (**b**) Nitrate concentration remaining in the soil at the end of the experiment, the initial concentrations were too small to represent graphically. In both graphs the initial concentrations of nitrates and ammonium in NPK fertiliser are not shown. The letters on top of each bar show that there is a significant difference ($p<0.05$) between the

treatments, whilst the same letters mean that there is no significant difference. Each bar represents a mean (± SE).

4.2.3 Leaf nitrate and ammonium content

To determine the form of nitrogen taken up by plants, the concentration of nitrates and ammonium in leaves was measured for each treatment. The concentration of nitrates in leaves was found to be higher than that of ammonium in all treatments. The nitrate concentration in the leaves from the NPK fertiliser treatment was not significantly different from that of the FC treatment, but it was significant when compared with FWC, CM and C. The nitrate concentration in FC was not significantly different when compared to the nitrate concentrations in other treatments. However, looking at the actual mean concentrations of nitrate in the leaves, NPK fertiliser had a very high concentration as compared to FC. In order of decreasing concentration FC, FWC and CM had higher concentrations of nitrates in comparison to the C (Fig 6). Amongst all treatments, the difference in ammonium concentration was not significant (Fig 6).

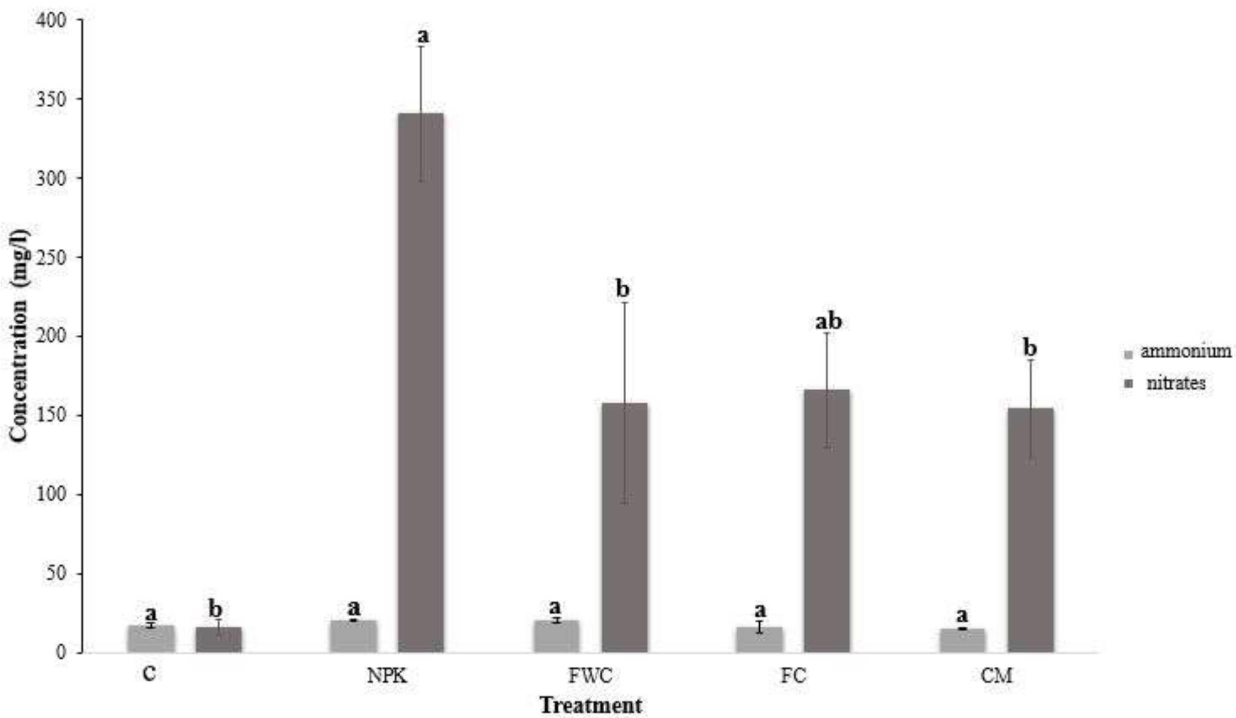

Figure 6. Leaf ammonium and nitrate concentration after harvest shown in mg/l. The letters on top of each bar show that there is a significant difference ($P<0.05$) between the treatments, whilst the same letters mean that there is no significant difference. Each bar represents a mean (± SE).

4.2.4 Phosphorus content in soil and leaves

There was no significant difference in leaf phosphorus concentrations amongst all treatments. Soil phosphorus concentrations were significantly higher in CM, FC and NPK than in C. The soil phosphorus concentrations in FWC were not significantly different from all other treatments (Fig 7).

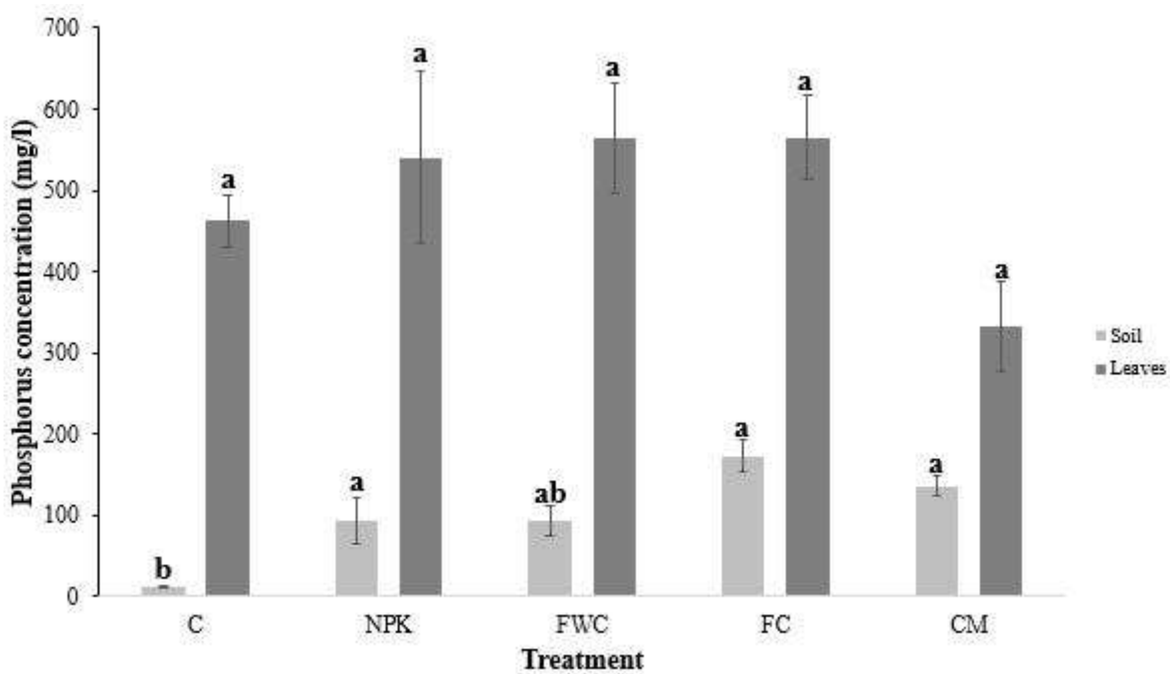

Figure 7. The concentration of Phosphorus accumulated in the leaves and in the soil. The letters on top of each bar show that there is a significant difference ($p<0.05$) between the treatments, whilst the same letters mean that there is no significant difference. Each bar represents a mean (± SE).

4.2.5 Content of macro and micro-elements in the leaves

The differences in potassium concentrations were significantly lower in FWC and C as compared to the other treatments (Table 2). The NPK treatment had significantly lower sulphur concentrations as compared to the FC and CM treatments which had the highest concentrations. The sulphur concentrations in FC and CM were significantly higher than in NPK, whilst C and FWC were not significantly different from the other treatments (Table 2).

Table 2. Concentrations of other macro and micro nutrients in the leaves. Within rows, means that are followed by different letters are significant ($p<0.05$), and those with the same letters are not significant ($p>0.05$). Each value is a mean from each treatment.

Treatment	C	NPK	FWC	FC	CM
Potassium	3660^{b}	7220^{a}	4970^{b}	6460^{a}	6750^{a}
Magnesium	539^{a}	614^{a}	503^{a}	596^{a}	635^{a}
Sulphur	117^{ab}	79.5^{b}	96.5^{ab}	152^{a}	137^{a}
Calcium	81.5^{a}	39.8^{b}	31^{b}	29^{b}	29.5^{b}
Sodium	1323^{bc}	655^{c}	2820^{a}	1230^{bc}	1650^{b}
Chlorine	2540^{ab}	1040^{c}	3010^{a}	188^{bc}	2660^{ab}
Manganese	2.83^{b}	8.4^{a}	4.98^{b}	3.55^{b}	4.05^{b}
Boron	0.84^{b}	1.65^{a}	0.74^{b}	0.785^{b}	0.67^{b}

Copper	0.29^{ab}	0.24^{b}	0.32^{ab}	0.35^{a}	0.27^{ab}
Iron	2.33^{a}	1.55^{a}	1.23^{a}	1.33^{a}	1.63^{a}
Zinc	6.2^{a}	5.18^{ab}	4.3^{b}	4.05^{b}	3.55^{b}
Molybdenum	0.12^{ab}	0.07^{b}	0.09^{ab}	0.13^{ab}	0.17^{a}
Aluminium	0.17^{a}	0.11^{ab}	0.1^{ab}	0.05^{b}	0.07^{ab}

4.2.6 Content of macro and micro-elements in the soil

The concentration of potassium was significantly lower in C as compared to the CM, FC and NPK treatments, but was not significantly different from FWC. The sulphur concentration was significantly higher in NPK as compared to the other treatments. Sulphur concentrations were also significantly higher in the CM treatment in comparison to C and FC, but were not significantly different in comparison to FWC (Table 3).

Table 3. Concentrations of other macro and micro nutrients in the soil. Within rows, means that are followed by different letters are significant ($p<0.05$), and those with the same letters are not significant ($p>0.05$). Each value is a mean from each treatment.

Treatment	C	NPK	FWC	FC	CM
Potassium	27.8^{c}	150^{b}	75.8^{bc}	154^{b}	305^{a}
Magnesium	49^{c}	68^{c}	49.3^{c}	109^{b}	141^{a}
Sulphur	68.3^{d}	305^{a}	144^{bc}	96.3^{cd}	171^{b}
Calcium	1330^{b}	1530^{a}	1420^{ab}	1210^{c}	1400^{b}
Sodium	20^{b}	24^{b}	149^{a}	35.5^{b}	124.8^{a}
Chlorine	11.5^{c}	32.3^{bc}	339^{a}	29.8^{bc}	140^{b}
Manganese	0.43^{c}	1.23^{a}	0.58^{bc}	0.5^{bc}	0.95^{ab}
Boron	0.25^{c}	1.05^{a}	0.3^{bc}	0.3^{bc}	0.5^{b}
Iron	87^{b}	90.8^{ab}	87.3^{b}	89.5^{ab}	99.8^{a}
Copper	1.13^{b}	1.83^{a}	1.1^{b}	1.33^{ab}	1.28^{b}
Zinc	3.5^{b}	4^{ab}	4^{ab}	5.75^{a}	6^{a}
Molybdenum	0.65^{a}	0.59^{a}	0.57^{a}	0.61^{a}	0.63^{a}
Aluminium	0.83^{a}	0.78^{a}	0.65^{a}	0.53^{a}	0.48^{a}

4.2.7 Soil concentration of micro-flora

To investigate the extent of microbial activity in the various treatments, the concentrations of bacteria and fungi were determined. There was significantly higher bacterial concentration in FWC, FC and NPK compared to CM. Bacterial concentration in C was not significantly different as compared to the other treatments (Fig 8). For fungal colonies, CM had significantly higher concentrations followed by NPK and FWC whilst FC and C had significantly lower concentrations of colonies (Fig 8).

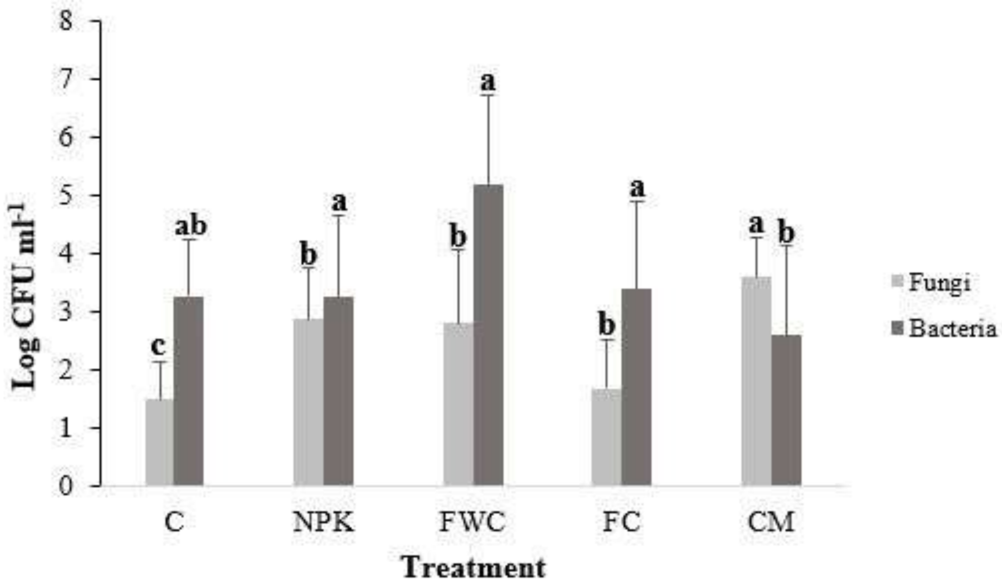

Figure 8. Bacterial and fungal concentrations in CFU/ml of soil from the treatments after the experiment. Different letters on top of each bar show that there is a significant difference ($p<0.05$) between the treatments, whilst the same letters mean that there is no significant difference. Each bar represents a mean (± SE).

4.3 Interviews

Respondents who participated in this study were between the age of 30 and 60 years old. Only one respondent was female and the other four were male. All the respondents had at least a university degree, four of them were PhD holders and they were fully employed in their respective countries at the time of the interviews. The interviewer was male, aged 24 years old and he was from Zimbabwe, a sub-Saharan Africa country.

4.3.1 Current methods used to enhance soil fertility

4.3.1.1 **Uganda**

In Uganda most farmers practice crop rotation as a way of managing soil fertility. They also leave crop residues on the field until the next cropping season. Manure from cattle and chicken are used by those who have access to them; but most small holder farmers have difficulties in gaining access to these types of manure. This is because in rural Uganda, both cattle and chicken are free range and they deposit the manure far away from households where they will be grazing or looking for food. Chemical fertilisers are not commonly used by smallholder farmers, because they are very expensive. Farmers also believe that chemical fertilisers destroy the soil hence they are afraid of using them.

"…they also have this, I can call it a myth, where they think that if they use mineral fertilisers on their field, it sort of like destroys the field, and if you use the mineral fertiliser then you have to continuously use it." Lecturer involved with consultancy.

It was not very clear who supplies the chemical fertilisers, the government or private companies, but it was made explicit that chemical fertilisers are extremely expensive and they are also of low quality.

Tanzania

In rural Tanzania, animal manure is sparsely used because of free range grazing systems which make the collection of dung cumbersome. Crop residues are rarely incorporated into the soil as they are either burnt whilst on the field or they are collected and burnt outside the fields. However, in most cases farmers cultivate on *new* marginal lands when their original plots lose productive capacity since no nutrient replenishment methods are used. In Tanzania, there are two ways of accessing chemical fertilisers: through the government fertiliser scheme or through private companies. Chemical fertilisers from the government are subsidised and they are difficult to access due to high levels of corruption, whereby people in influential positions grab everything, leaving none or just a little for the poor smallholder farmers. Poor infrastructure was highlighted to be a major hindrance for fertiliser delivery to remote areas where most poor smallholder farmers live.

Ethiopia

In Ethiopia chemical fertilisers are subsidised, and it is alleged that all farmers have access to fertilisers which are solely supplied by the government on a loan basis.

"…one way or the other almost all farmers use mineral fertilisers." Professor working with land and water management

However, it was indicated by the respondent that farmers struggle to pay off the fertiliser loans which are then written off by the government. The fertiliser supply in Ethiopia was also said to be not very efficient as seen by the deferred supply, whereby in most cases fertilisers are availed later than they are actually needed by the farmers. Cattle dung is used as a source of fuel for cooking since wood is scarce, hence it cannot be used for agricultural purposes. Other potential sources of manure were not discussed.

4.3.2 Compost use

In all three countries some form of composting is done, but it is not systematic, organic matter is just put in a pile for some time and at times it is turned, but it is usually not monitored. In Uganda there is wide evidence of composting projects being carried out at Makerere University in collaboration with Kampala city council. In this collaboration, organic waste from different parts of the city is collected and vermicomposted. Only a few urban farmers who are aware of the benefits of composting waste participate in these projects. Worms from the vermicompost are sold for an income. Commercialisation of organic fertilisers from the vermicompost was tried but it failed. This is because farmers are deterred by its bulkiness and low nutrient concentration.

"…one of the reasons they [farmers] do not engage so much in composting is because they feel that the nutrient levels are not high enough because they have to apply so much." Lecturer involved with consultancy.

After the commercialisation failed, they tried to give it freely to urban and peri-urban farmers but there was resistance due to the already highlighted reason, bulkiness. Organic fertilisers from biogas plants are also unattractive to farmers as they contain a lot of weed seeds which may give problems to farmers.

4.3.3 Use of excreta

Uganda

In Uganda fertilisers of faecal origin are mainly used for garden lawns or flower production by affluent people. However, there have been various projects aimed at encouraging the use of human excreta by urban and rural farmers. In these projects, known as ecosan projects only a few farmers participate, for various reasons. Most farmers are tired of participating in projects from which they do not get any immediate benefits and for this reason, they want direct payment to participate in any project.

"…when you bring for them a project, it's like it is your project. They do not have the ownership of the project, like say, 'it is our project', to improve their livelihoods," Lecturer involved with consultancy.

"…now if you are taking a project, you have to sort of bribe the farmers because the farmers will ask you, 'now where do I benefit?' and by benefiting it means something, you have to give him something now for him to give you his time," Lecturer involved with consultancy.

"…maybe it is because of attitude, we come and promise farmers so much and then afterwards we do not fulfil our promises with the farmers, especially researchers because as soon as they get their data that is the end of it. They do not inform farmers what has happened yet at the beginning they had promised farmers heaven on earth," Lecturer involved with consultancy.

Some farmers only participate out of curiosity and they resort to their old systems as soon as donors leave. One of the major issues with these EcoSan projects is that people do not want to do anything with faeces because they think that it is filthy and should be disposed of as far away as possible hence acceptance has been extremely low. People are not even open to talking about faeces. They are disgusted at the sight of it, above all, it is a taboo to touch or work with faeces. Most cultures in Uganda perceive faeces as something bad and its use in agriculture can never be tolerated. People are also scared of working with excreta for health reasons. There are EcoSan toilets which allow access to toilet waste and this makes many people paranoid as they think that their enemies might access their faeces for sorcery purposes. For example, generally in rural Uganda pregnant women do not use toilets for fear of their unborn babies being bewitched.

The few farmers that have been shown to accept using faeces in agriculture do not do so easily. A lot of sensitisation is done and there exist demonstration plots where farmers see the benefits of using excreta. Of the total number that attend these plots, only an estimated 5% are thought to use excreta on their own farms. Most people claim that they cannot eat food produced using faeces as a fertiliser, but paradoxically, there is lot of crop theft at demonstrations plots which use excreta as a fertiliser.

"…what surprised us is that when we grew maize in demonstration plots, when it was maturing, some people were stealing it." Extension worker from Uganda

Those few who adopt excreta, they have EcoSan toilets; they collect faeces from their toilets and compost it in pits for 1-3 months before application on maize and banana crops. In addition to faeces, these farmers also use urine as a fertiliser.

In Tanzania, the interviewee thought that there was not any use of excreta in the agriculture sector. The respondent cited that people would not want anything to do with faeces as it is culturally seen as unclean. However, the respondent thought that people would take it up if they are educated and shown the benefits of using excreta.

In Ethiopia, the respondent cited it to be impossible to use excreta in agriculture. It is a taboo to work with faeces, it is even culturally unacceptable to talk about faeces.

"If you gather a group of women and tell them that you are going to discuss faeces, they will just disperse." Professor working with land and water management.

There was an EcoSan project that failed to take off because Ethiopia has a very strong Christian Orthodox and Muslim religion which both condemn the touching of excreta once it is ejected.

"…culturally, by the way, Ethiopian people can be considered as Christian Orthodox who are very conservative and also the Muslim communities which are equally conservative. All religions are against meddling with faeces." Professor working with land and water management

In the three African countries represented in this study, especially in Ethiopia and Uganda with some parts of Tanzania, access to toilets is limited. In such cases it is common for people to use bushes or squat holes which they dig in their fields and defecate in at dawn or at dusk when there is a little bit of 'privacy'. All respondents indicated that use of faeces as fertiliser may not be a problem since people defecate in their fields; the only problem is with handling it like in the way proposed in this thesis.

In all three countries, women were highlighted to play a crucial role in agriculture as they are the ones who usually work in agriculture, plant, weed and harvest. According to the respondents, women are responsible for all household duties, including the maintenance of sanitation facilities. It was suggested by respondents from Ethiopia and Uganda that women are the ones to approach in order to successful introduce the use of excreta in the agricultural systems of SSA.

5 Discussion

5.1 Agricultural System

This study was done basing on the Social-Ecological Systems Framework (SESF).In this section the results from the pot trials and the interviews will be discussed in accordance to the ecological and social system parts of the framework, respectively. Some components of the social-ecological system (agricultural system) identified during the study and their interrelationships are presented in Fig 9.

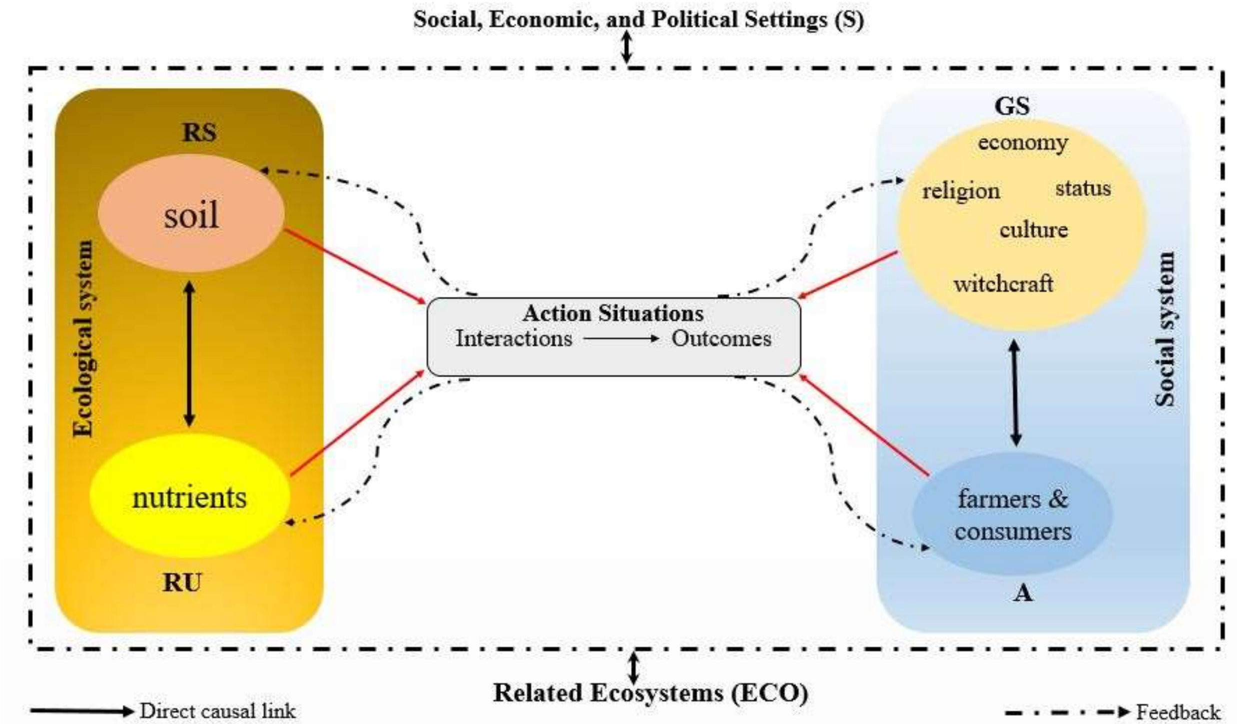

Figure 9. Social ecological systems framework with various components identified during the study. RS: resource system, RU: resource units, GS: governance systems, A: actors. *Source: Author*. *Adapted from (Ostrom, 2009)*

5.1.1 Action situations

In order to investigate the effect of BSF composted human faeces on the availability of nutrients, their uptake by plants, and the subsequent plant growth (outcome), there was need to carry out pot trials in the greenhouse (action). This was done by the author, and in this context, he was an 'actor'.

5.1.1.1 **Outcomes (yield)**

From the results, both the fresh and dry weight of leaves harvested from the NPK treatment was not significantly different from that of leaves from the FC and FWC treatments. In general, the nutrient availability and uptake in FC and FWC treatments were not significantly different from the NPK treatment, hence resulting in similar plant growth and yield amongst the three treatments. In a similar study, in Harare, Zimbabwe, humus derived from Forsa Alterna[8] pits significantly boosted vegetable crop yields, up to four times higher as compared to unfertilised plots with poor soils (Winblad & Simpson-Hébert, 2004). In another study done by Guzha *et al.* (2005) in Marondera district Zimbabwe, human faeces, human faeces+urine and NPK+ ammonium nitrate fertiliser were used as nutrient sources for maize in field trials. According to their results, human faeces gave the best yields as compared to the other forms of fertilisers used in their study. However, in their methods, Guzha et al. did not state how exactly they determined the quantities of each fertiliser added to the maize crop, they just stated the amounts added and this makes it difficult to actually compare the effect of the fertilisers since they might have contained different amounts of nutrients. Despite this drawback, the results in the present study and that of Guzha et al., strongly indicate that human faeces have the potential to give very good yields if applied as a fertiliser in the right amounts on poor soils. Furthermore, comparing yield from the FC and CM treatment, this experiment showed that the former gives better yields than the latter which is usually used/preferred by farmers.

5.1.2 Ecological system

The soil is an intricate living, dynamic system that is made up of various components and processes and it is an ecosystem on its own (Gliessman, 2007). Nutrients are resource units which are the major component of interest in this study. Black soldier fly composted faeces is a source of these nutrients, but they are *locked* inside the faeces. However, the action of microflora and other organisms found in the soil ecosystem can unlock these nutrients and make them available in the resource system (soil). In this section, it will be analysed if these locked-up nutrients were actually availed in the resource system by the action of these microflora.

5.1.2.1 **Nutrients in soil and leaves**

The concentration of soil nitrates in organically fertilised treatments was low at the beginning of the experiment, but was found to have increased at harvest. This suggest that there was significant mineralization of organic nitrogen for all treatments with organic fertilisers, however nitrification could have taken place as well. The concentration of soil ammonium was high in FC, FWC, and CM, at the beginning of the experiment, but it had reduced to low levels at harvest. This could have been due to volatilization or nitrification. Uptake of ammonium by plants could have been possible but this is unlikely since nitrate is the primary nitrogen form taken up by most plants including Swiss chard (Kolota & Czerniak, 2010; Matallana Gonzalez *et al.*, 2010; Benton Jr,

[8] Forsa Alterna pits are pits where both urine and faeces are mixed.

2003). In the leaves, the concentration of ammonium was found to be extremely lower than that of nitrates. This is probably because nitrate is usually the form of nitrogen stored in the leaf cell vacuoles by plants (Benton Jr, 2003; van der Leij *et al.*, 1998). There was no significant difference in leaf ammonium concentrations for all treatments. As for nitrates, there was no significant difference between the FC and NPK treatments. According to the results from this study, nitrogen availability and uptake between FC and NPK was not significantly different. This shows that BSF composted human faeces as a fertiliser can meet plant nitrogen requirements in a similar way to mineral fertilisers, hence they (faeces) could be used by farmers in SSA as an inexpensive source of nitrogen.

Soil sulphur concentrations were significantly higher in the NPK treatment as compared to the other treatments. However, this did not tally with leaf sulphur concentrations where they were significantly higher in FC and CM as compared to the NPK treatment. An interesting relationship between the concentration of sulphur and that of nitrates was found. Leaves from the NPK treatment simultaneously had the highest and lowest concentrations of leaf nitrates and sulphur respectively whilst leaves from the control treatment had very high sulphur concentrations and the lowest nitrate concentrations. It seems that low sulphur concentrations resulted in higher nitrate concentration in NPK as sulphur shortages are believed to inhibit the use of the availed nitrogen resulting its accumulation (Ceccotti & Messick, 1994; Schnug, 1990). This is because nitrogen and sulphur are involved in the synthesis of proteins and the shortage of one results in the accumulation of the other (Schonhof *et al.*, 2007). In the organic fertilisers the concentrations of nitrates was higher than that of sulphur but the difference was not as wide as for the other two treatments. This is probably because the supply and uptake of the two nutrients by organic fertilisers could have been close to balanced or optimum proportions. This may suggest that sulphur concentrations in FC might not have limited plant development nor yield. However, it is difficult to ascertain if this relationship between nitrates and sulphur affected yield or not, hence it would be necessary to investigate the tissue composition of the two nutrients in order to draw a sound conclusion.

The difference in concentration of soil available phosphorus was not significant for any of the fertilised treatments, but there was a significant difference when they were compared with the control. The soil available phosphorus in the control treatment was almost depleted whilst it was still in abundance in soil from the other treatments. Leaf phosphorus concentrations were not significant for all treatments, including the control. However, leaf phosphorus concentrations for the control treatment were a bit higher than those in CM, despite the latter having higher soil phosphorus concentrations. An explanation for this phenomenon could be attributed to the higher microbial activity in CM, which could have competed for phosphorus with the plants. Microbes have been suggested to affect the availability of phosphorus to plants through immobilization as they incorporate it[9] into their own biomass (Sylvia *et al.*, 1998). However, findings from this study

[9] phosphorus

show that phosphorus availability and uptake in the fertilised treatments were not significantly different and did not affect yield. This suggests that FC is a good source of phosphorus for plant growth.

For the other nutrients, only the differences in availability and uptake of manganese (Mn) and boron (B) between FC and NPK treatments were noteworthy. The concentrations of the two nutrients were significantly higher in the soil and leaves from NPK than in FC. However, it is difficult to tell if these findings could have influenced the slight, but not significant yield difference between NPK and FC. There were also many other micronutrients at play whose concentration differences were not significant but might have influenced yield. However, the concentrations of these other micronutrients might not necessarily have a linear relationship to yield due to the complex interactions and processes that take place in the soil ecosystem during nutrient uptake and utilisation by plants.

5.1.2.2 **Microflora in the soil**

Soil microflora play a crucial, indispensable role in the soil ecosystem, they are closely related to plant growth and play an important role in the nutrient cycle by mineralising or immobilising nutrients (Sylvia *et al.*, 1998; Waksman & Starkey, 1931). Soil microflora require nutrients for growth, they either acquire them from readily available nutrients in the resource system or they decompose organic substances in order to get them (Sylvia *et al.*, 1998). The difference in soil bacterial concentrations amongst FC, FWC, NPK and C was not significant, however all four had significantly higher bacterial concentrations as compared to CM. Bacteria could not grow much in the CM treatment probably because of the higher fungal growth which dominated in this treatment, resulting in low nutrient acquisition by bacteria, hence affecting their[10] growth (Waksman & Starkey, 1931). The concentration of fungi was significantly higher in CM as compared to the other treatments. This is probably because cow manure unlike the other fertilisers contains a lot of complex molecules like cellulose, lignin, etc. which are very well decomposed by fungi than bacteria (Waksman & Starkey, 1931). However, the concentration of bacteria or fungi in the soil ecosystem is affected by a number of factors other than the source of nutrients, for example, a slight difference in pH or salinity may have significant impact on microflora quantities (Fierer & Jackson, 2006; Waksman & Starkey, 1931). This makes it challenging to get a clearer idea on how the concentration of microflora in soil from different treatments might have influenced nutrient availability. Despite this, it is evident that the concentration of microflora in the FC treatment managed to avail adequate nutrient quantities that were required for plant growth as seen from the FC yield which was not significantly different from that of NPK[11].

[10] bacteria
[11] NPK was used for comparison because it was thought to give optimum yield.

5.1.3 Reflections on Methods used in the experiment

The greatest issue with this study was the use of the greenhouse. Conditions in the greenhouse were all controlled, ignoring the actual dynamics that exist in complex natural environments. This imposes restrictions on the realism of results obtained from such experiments (Gibson *et al.*, 1999). Despite the issues, the experiment allowed the evasion of constraints associated with natural complex plant environments (Gibson *et al.*, 1999), which could have made it difficult to analyse the effects of the different fertilisers investigated on plant growth. This approach was quite useful as it allowed construction of predictive models that could be applied in nature (Tilman, 1987), through extrapolation from the particular to the general (Keddy & Shipley, 1989). The complete random block design used in the experiment was meant to try to have unit uniformity in blocks so that the differences observed between treatments would be largely determined by differences between treatments. This was meant to help get as much realistic results as possible from the study.

The method that was used for yield analysis was mainly quantitative, more value was put on the weight of accumulated biomass. It would have been helpful also if the dietary nutritional value of the harvested crop had been determined to actually see which fertiliser was most suitable for plants so that they would meet human dietary needs. However, this was compensated by leaf sap analysis which examined the quantities of nutrients taken up by plants. Plant sap analysis gave an overview of the nutrients that were readily available in the plant that could be used for its growth and development (Timmermans & Ven, 2014). This type of analysis managed to meet the requirement of the experiment of seeing how much of the soil available nutrients, plants would be able to take from the soil for their development. The Spurway method used for the soil analysis was important to give general information on the quantities of more or less soluble nutrients that were available to the plant at the time the soil test was carried out (Spurway & Lawton, 1949). However, this test might not have been able to give the total quantities of soluble nutrients that were available in the soil solution as well as those on the soil exchange complex at the time of testing (Spurway & Lawton, 1949).

Microbial analysis was useful to determine the concentration of microflora hence an estimate of how much they might have affected nutrient availability. However, the analysis fell short of determining the quantities of the actual microflora that was useful in availing nutrients for plant uptake.

5.1.4 Semi-structured interviews

5.1.4.1 **Current methods used to address nutrient depletion**

In all three countries the use of mineral fertilisers was shown to be a challenge for various reasons, the major one being their cost. Mineral fertiliser costs are seen as a burden by farmers, in Uganda, for example, farmers fear using them as they believe that they will have to continue buying fertilisers once they start using them on their fields. In Ethiopia, where mineral fertilisers are subsidised and are given to farmers on a loan basis by the government, farmers usually have trouble paying back these fertiliser loans, likely putting them under economic stress. Strangely enough, with all this compelling evidence showing that mineral fertilisers are not suitable for SSA, some external institutions (**S**[12]) like the World Bank and the IFDC[13] still push for their use in the region (WorldBank, 2013; Michael, 2007). This is despite the failure of mineral fertiliser use in SSA around the 1980s when African governments directly subsidised fertilisers. Instead, the World Bank has suggested that the private sector must step in, to improve efficiency in supply and marketing of mineral fertilisers (Michael, 2007). This approach is likely to fail as well since the issue is not really about who supplies the fertilisers or about efficiency in their supply. The root problem is an external socio-economic factor, poverty, which makes farmers in SSA incapable of purchasing these mineral fertilisers in order for them to produce enough food for themselves.

Crop rotation and the incorporation of crop residues used in Tanzania and Uganda are good methods to try to recycle nutrients, but they are inadequate to balance the nutrient quantities extracted from the resource system (soil). Access to animal manure was highlighted to be a challenge for most farmers and the amount of manure applied is not enough to replenish those nutrients lost through harvests. In Uganda farmers rejected vermicompost, saying it was too bulky with little concentration of nutrients. These challenges suggest that a different approach towards addressing soil fertility issues in SSA is required.

5.1.4.2 **Use of human faeces**

From the information gathered through interviews only a few people in SSA were shown to accept using human faeces in agriculture whilst the majority shunned it. This is because there are a set of actions that are 'allowed' or 'not allowed' when it comes to its use. The use of human faeces is a 'problem metaphor' of which various actors perceive, and behave, towards differently. Underlying the various behaviours towards the use of human faeces in agriculture are a number of governance systems and other factors which determine how people perceive and relate to things (Fig 10).

[12] Social, Economic, and Political Settings (S)
[13] International Fertiliser Development Centre.

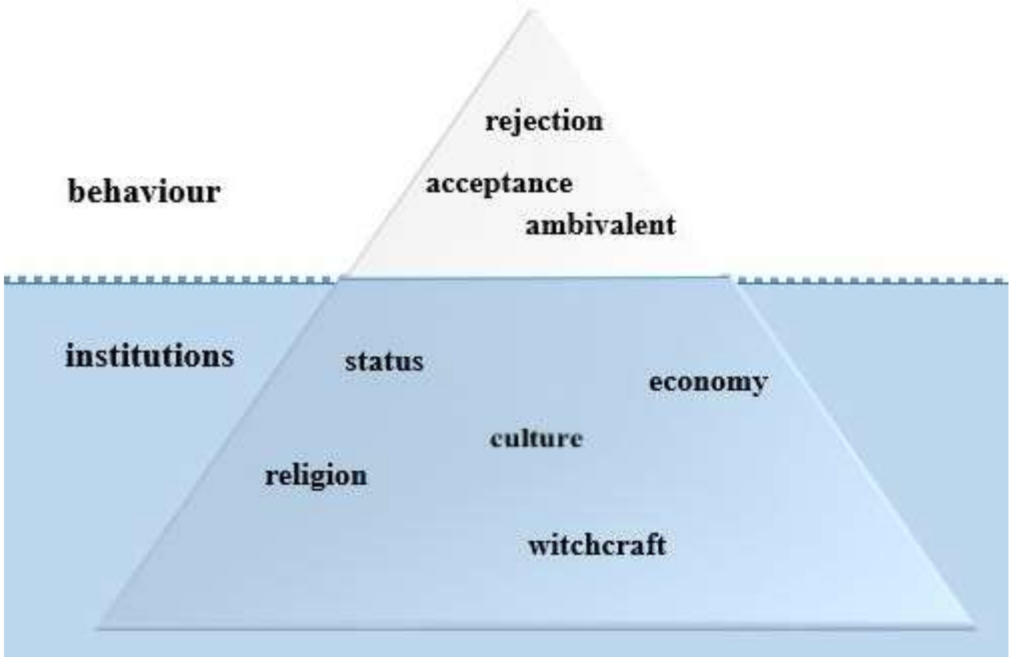

Figure 10. Cultural Iceberg Model. *Source: Author. Adapted from Hall (1976).*

Acceptance

The ones who accepted and embraced the use of their own faeces, did it because they had realised the benefits of using faeces in agriculture, through participation in ecosan projects led by various non-governmental organisations. These benefits were realised as a manifestation of poverty, which is a socio-economic institution. According to the respondents, farmers realised that they could simultaneously save economic costs from purchasing mineral fertilisers and increase their yields if they used their own faeces as a fertiliser to boost crop production. Such benefits were also once widely recognised in Tamale and Bolgantanga, Ghana where farmers used to use sewage sludge to maintain soil fertility and to get good yields (Cofie *et al.*, 2005).

Rejection

For the ones who were reported to shun using human faeces, the problem of using it was unique to each group depending on the conceptual systems or other factors that governed their perceptions. Various institutions like religion, culture and witchcraft were identified to have strong negative influence on the people's willingness to adopt the use of human faeces for agricultural purposes. The religious aspect associated with the use of human faeces makes acceptance difficult because in such religions, people cannot reason beyond religion, *"religion is the law"* (Refsgaard *et al.*, 2006). Meddling with faeces was strongly highlighted as a cultural taboo, since human faeces are perceived as waste or dirt. This cultural conception of faeces was also highlighted by Refsgaard *et al.* (2006), to be a challenge when it comes to the use of human excreta in agriculture. Fear of being bewitched seem to be of concern if SSA. There are reports that peri-urban farmers in Zimbabwe were reluctant to use their own faeces for agricultural purposes because they thought they would be bewitched if their enemies got hold of their faeces (Guzha, 2004). In such communities, people believe that faeces have to be disposed of far away from the household (Guzha, 2004). Other people saw using faeces as socially degrading, they thought that it is the ‘worst’ one could do.

Ambivalent

Some people in Uganda were reported to be stealing crops fertilised using human faeces, despite the fact that they had refused to use human faeces to fertilise their crops. However, it could not be ascertained during the interviews, why these people acted in such a way. There could be a couple of reasons for this:

1. They were too desperate for food, but at the same time handling faeces to use as fertiliser for their own crops might have been a problem for them, but they did not mind eating food fertilised using human faeces.
2. It is possible that they were curious to know what the food fertilised using human excreta tasted like.
3. Another possibility is that these people could have been too embarrassed to use faeces on their crops as the society would judge them (persona values versus societal norms).

5.1.5 Reflection on interview methods

Semi-structured interviewing, a major tool in participatory rural appraisal (PRA) approaches was the main method used for exploring stakeholders concerns and perceptions. Such a knowledge generating method was indispensable when it comes to in-depth inquiry into complex social systems, where problem metaphors are a common feature. For example in this case various groups in society perceived the use of excreta in agriculture differently; and this difference in perception was rooted in people’s different conceptual systems. The open-ended and discursive nature of semi-structured interviews encouraged respondents to share as much information as they could, bringing up new themes unanticipated by the interviewer. This allowed an iterative process whereby themes brought up in preceding interviews were incorporated and explored in subsequent ones (Bryman, 2012). Interviewer’s flexibility and eagerness to learn allowed follow up questions to be asked in pursuit of emergent themes.

Due to travelling challenges to SSA, some of the interviews had to be carried out over the phone whilst others were done face to face. Phone interviews were a very cheap and time saving way of gathering information (Bryman, 2012), from the relevant respondents located in Africa. Using, telephone interviews guaranteed interviewee anonymity likely resulting in improved reporting of sensitive issues (Lyberg & Kasprzyk, 1991).

A potential source of error from the interviews could be social desirability (Grenier, 1998), as interviewees might have wanted to portray themselves in positive light of the interviewer. For example in this study all respondents, agreed that they would not mind to consume or produce food using their own excreta, this positive attitude might have been a result of wanting to *please* the interviewer. However, it could also be attributed to their level of education which might have rendered a positive perception towards the use of human faeces in agriculture. Some of the issues that were raised during the interviews were politically sensitive and it is plausible that respondents were dishonest in cases where they had to critic their governments but failed to do so as they felt they had to be patriotic. This study fails to take into account of the immense spatial and cultural heterogeneity in SSA, only respondents from three of the forty-eight countries in the region were interviewed, reducing the representativeness of the information gathered.

5.2 Suggestions to facilitate adoption of human faeces

5.2.1 Participatory Rural Appraisal Approach

To successfully introduce the use of human faeces and its acceptance in agriculture, sensitisation is key. In a participatory manner, both farmers and consumers should be allowed to identify their concerns and be given room to address these concerns amongst themselves. This is a learning process which may be guided with the help of a facilitator as deemed necessary. Demonstration plots for farmers, managed by farmers would be necessary for them to practically learn and observe the whole process involved in using human faeces for agricultural purposes. This approach of allowing farmers to learn in a participatory and collaborative manner has been successfully used in Tororo district, Uganda, where farmers observed and evaluated the effects of urine on their crops (Andersson, 2015). Such an approach could result in the overshadowing of some cultural beliefs and myths as they may be proven to be untrue through the whole learning process. This may actually be achieved without telling farmers and/or consumers that their beliefs are nonsensical. However, when it comes to religion the issue could be totally different. Since the issue of food insecurity and malnutrition in SSA is a life threatening one, and needs to be immediately addressed, it would be necessary to consult and discuss the use of human faeces with the concerned religious leaders. This may help to identify the underlying reasons which may be influencing religious laws that prohibit interaction with faecal matter. Such a process might allow the identification of measures that could be taken to by-pass these religious '*limiting'* laws, finally resulting in the acceptance of human faeces by the concerned parties. This approach is similar to the one suggested by Warner (2004).

5.2.2 Women as important actors

In the three countries represented in this study, women were reported to be the major labour force in agriculture. They were also reported to be responsible for household sanitation and taking care of children. According to FAO (2011), most farmers in SSA are women and they are responsible for the production of 75% of the region's staple foods. Raising the productivity of women farmers has been considered crucial for the revitalization of the agricultural sector in SSA and the improvement of food security at household level (FAO, 2011; Saito *et al.*, 1994). This is important because women and children are the ones who mainly suffer from malnutrition (FAO, 2011). The problems borne by women in SSA are immense and challenging and it seems they can only be tackled if they (women) are empowered through the provision of resources that they require for agricultural productivity (FAO, 2011).

5.2.3 Black soldier fly composting of faeces by farmers

The introduction of BSF can be done at farm or household level and it will necessitate the establishment of ecological sanitation (ecosan) facilities. Sanitation facilities in SSA are scarce, as of 2015 as much as 70% of the population in the region practiced open defecation as they did not have access to toilets (WHO, 2015). The benefits of using BSF composted human faeces as a fertiliser may incentivise African governments, NGOs, communities and individual households to establish ecosan facilities so that people may be able to collect their faeces from such facilities. This will also help curb poverty related diseases like cholera, diarrhoea, typhoid, dysentery and hepatitis A amongst others, which claim hundreds of thousands of lives in the region (WHO, 2015). The construction of ecosan toilets should be in a manner that women feel safe when using them (Rosenquist, 2005), and also in a way that makes it easier for them to collect faeces for composting.

With the help of a facilitator, farmers can learn how to collect, handle, and compost their own faeces using BSF in order to produce their own fertilisers locally. However, there could be risk of spread of diseases, but this can be minimised or even eliminated if farmers adequately learn how to safely handle the faecal material during and after composting. Black soldier fly rearing might not be very feasible at household level as it requires a bit of maintenance and know-how. Community centres collectively managed by farmers could be set up to allow the easy rearing of BSF. Farmers will then collect early instar larvae from these centres whenever they need to compost their faeces or even food waste[14] (Fig 9). This attribute of cooperative/collective rearing

[14] Food waste might not be very common since the people struggle to meet their daily food requirements.

is important for rural development as farmers may easily be able to organise themselves in case of other problems that they might face as a community.

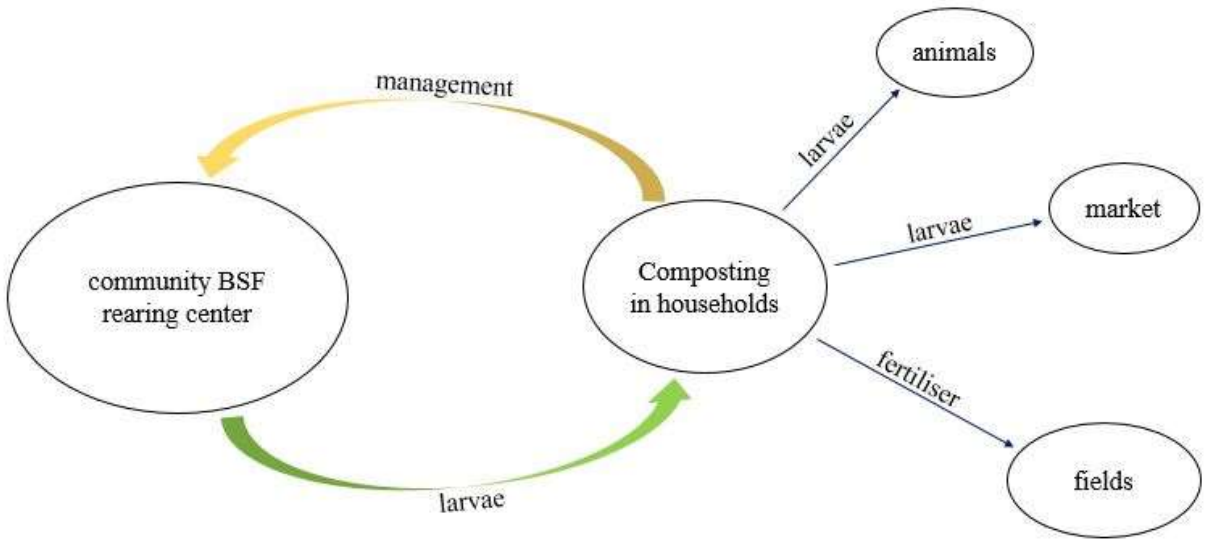

Figure 9. Community BSF rearing and management centre with composting at household level. *Source: Author. Adapted from (Diener et al., 2015)*

On average one person can produce up to 180 kg fresh weight of faeces per year (Refsgaard *et al.*, 2006), assuming that on average a family has six members, they could produce close to a tonne. Using BSF larvae for composting, the tonne could be concentrated to only around 170 kg dry weight, reducing the total inflow mass by up to 80 % on weight basis (Lalander, personal communication), making it easy to store and transport. After BSF composting, the compost residue does not have an offending odour and it does not look like faeces. This makes the use of BSF larvae composting attractive for use in agriculture as compared to other methods of composting where farmers are deterred by the faecal odour during field application. For effective fertiliser application, only about 16 grams of the fertiliser maybe added directly to the plant instead of broadcasting all over the field. However, assuming column spacing of 75 cm and row spacing of 30 cm, for maize (a common crop in SSA), the amount of faecal fertiliser produced by a family of six will not be enough to fertilise one hectare. In such a case, additional or complementary sources of fertiliser would be required.

The BSF larvae collected at the end of the composting period can be used as animal feed or fish meal as they have a high fat and protein content (St-Hilaire *et al.*, 2007). This would be very important for farmers who have mixed farming systems as they can fatten their animals, especially poultry, resulting in better selling prices for such animals. It is also possible for farmers to sell their BSF larvae directly to animal farmers as protein, this will increase their financial resources, helping to tackle some of the household level economic challenges.

5.2.4 Other advantages of using BSF compost

There are a lot of advantages associated with using human faeces in agriculture. Environmentally it is a very good way of recycling nutrients back to the field (Jensen *et al.*, 2005), preventing pollution of precious water resources (Langergraber & Muellegger, 2005; Rosenquist, 2005). It also contains organic matter which amends structure, texture, mineral and biological composition of the soil, improving its general health and fertility (Diacono & Montemurro, 2010; Omotayo & Chukwuka, 2009; Nardi *et al.*, 2004). As stated by FAO (2015a), a healthy and fertile soil is not only the basis for sustainable agriculture, but also the basis for rural development and agricultural productivity which are both fundamental elements in tackling poverty (FAO 2015b).

5.3 Concerns about hormones and pharmaceuticals

The issue of hormonal and pharmaceutical contamination from using human faeces as a fertiliser could be of concern to most people. However, for as long as there have been humans on earth, hormones from other mammals as well as humans were continuously and will continue to be excreted in the environment (Jönsson *et al.*, 2004). This fact should be one of the reasons why humans should not fear hormonal 'contamination' from using their faeces in agriculture. Such a notion of hormonal 'contamination' gives the wrong impression that we as humans do not belong to this natural environment, which hormones are a part of. Paradoxically, modern day animal production involves a lot of growth enhancing hormones, but many people seem not to be concerned with, or aware of this. According to Jönsson *et al.* (2004), plants and microbes are adapted to hormones and they are capable of decomposing them, hence no need to worry about hormones. Most pharmaceuticals are sourced from nature, even though some are man-made, the various microbes that exist in the soil are quite capable of degrading these medicines (Jönsson *et al.*, 2004). Apart from the soil microbes, BSF larvae were shown to reduce the half-life of commonly used pharmaceutical drugs including the antiepileptic substance carbamazepine, that has been shown to be very stable in aqueous environment (Lalander *et al.*, 2016). This suggests that the medicines will even be easier for the soil microbes to break down. With regards to bio-accumulation of pharmaceuticals in the larvae, no accumulation was noted in the larvae using the extraction methods applied by Lalander *et al.* (2016)

5.4 A reflection of the Concepts and Tools used in this study

5.4.1 Social-Ecological Systems Framework

The Social-Ecological Systems Framework (SESF) was indispensable in this study, it helped acknowledge the intense and complex coupling between the social and ecological systems, found in agricultural systems (Fig 9). The issue of soil nutrient depletion is an ecological system (soil) problem which results in hunger, malnutrition and food insecurity of actors at the social systems level. The proposed solution of using BSF composted human faeces as a source of soil nutrients is noble. However, it requires intervention by humans who will have to apply the fertiliser on the fields in order to get the desired outcome of improved yields. This shows how the framework was useful in the identification of a range of functional variables and their crucial relationships which are essential to focus on, when considering human faeces as a solution to a social-ecological systems problem.

Despite the merits of the framework, it restricted in-depth investigation into ecological and social systems associated with use of human faeces in agriculture. This is because the SESF avoids the horrendous simplification of one system over the other.

5.4.2 Hard Systems Methodology

The issue of nutrient deficiency in SSA soils is a real world problem that needs '*fixing*'. With a systems engineering approach, the issue was formulated in terms of the required state of nutrient replenishment, S_1; and that of the current state of nutrient depletion, S_0, and a number of ways or methods of transitioning from S_0 to S_1 were identified. Using systems analysis, these methods were scrutinised in order to identify the most lucrative method which could fulfil the desired goal of replenishing nutrients in a sustainable way. The use of BSF composted human faeces was identified as the most lucrative method to address the problem of soil nutrient deficiency in SSA. However, it was crucial to test if it was the best option for transitioning from S_0 to S_1 and this was done using pot trials. In this respect, Hard Systems Methodology was quite useful in this study.

5.4.3 Soft Systems Methodology

In this study, the application of Soft Systems Methodology was important in identifying the various invisible social structural variables and other factors which determine actors' patterns of interactions (behaviour). This enhanced the understanding of how actors might evaluate the trade-offs of the "perceived costs and benefits" associated with using human faeces against their own conceptual systems and other factors which structure their behaviour. This allowed a problem formulation process in which it was demonstrated that individuals' different ways of perceiving human faeces were equally rational.

This study took a realist approach to enable the identification of '*what'* are the 'causal powers' or 'liabilities' that underlie emergent powers which influence social system dynamics. Even though the approach is in admission to that *emergent powers* arise from lower level mechanisms (causalities) (Cumming, 2011), it failed to explore the deeper complexities of the meanings, structures and relationships that govern these causalities. To understand, the complexity of social systems holistically, it would have been necessary to take a constructivist approach which is actually capable of understanding the meanings embedded in the causalities (Robson, 2011). However, such an approach necessitated several cumbersome studies, hence it was beyond the scope of this thesis.

5.4.4 Agroecology

An agroecological perspective allowed the use of a holistic approach, considering ecological, economic, political and social dimensions that are affecting agriculture in SSA, by looking at the various components of the agricultural system in the region. The study focused on finding the best possible ecological concepts and principles that could be used or applied in the sustainable management of agroecosystems, simultaneously addressing the socio-economic needs of the affected people. In the context of this study, recycling nutrients by using human faeces was such an ecological principle and concept.

6 Conclusion

From a social system perspective of the study, people from Ethiopia, Tanzania and Uganda were interviewed and they helped identify the potential challenges regarding the adoption of the use of human faeces in agriculture by people in sub-Saharan Africa. A number of governance systems such as religion, culture, personal values and witchcraft; and factors like fear of contracting diseases and bad faecal odour were highlighted as potential hindrances to the adoption of human faeces as a fertiliser. However, despite these potential challenges, other factors that could incentivise people to adopt the use of their own faeces for agricultural purposes were also identified. These included the saved economic costs from buying expensive mineral fertilisers, and the high yields that could be attained through the use of human faeces.

From an ecological system perspective, this study demonstrated that crops fertilised using black soldier fly larvae composted human faeces can give significantly high yields as compared to non-fertilised crops. It was further demonstrated that BSF composted human faeces can give similar yields to those obtained from crops fertilised using mineral fertilisers (NPK), which are commonly thought could give best crop yields. This strongly suggests that BSF composted human faeces could be indispensable to poor smallholder farmers in SSA as a very cheap source of plant nutrients, contributing to increasing agricultural productivity, evading food insecurity, hunger, undernourishment, and above all poverty reduction. The possibility of selling BSF larvae as protein feed would also improve the economic situation of these poor farmers. All these noble factors associated with the use of BSF composted faeces for agriculture should be taken into consideration by all stakeholders trying to push for sustainable agricultural development in sub-Saharan Africa.

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