The influence of agroforestry on soil fertility in coffee cultivations

A review and a field study on smallholding coffee farms in Colombia.
Abstract

Coffee is, together with cacao, the crop most commonly cultivated under shade trees in order to cope with physiological stress (as drought and sun radiation) and erosion as well as to generate additional income for the farmer. However, today this agroforestry coffee management is increasingly transformed into industrial plantation with little or no shade using varieties that tolerate full sun and can be planted with higher density. This conversion most often brings an intensified use of external input, such as fertilizers and pesticide, and a reduction in biodiversity as well as long term soil fertility.

The objective of this study was to examine whether the inclusions of trees in coffee cultivations favour soil fertility and how it affects the output of the system. The aspect of output was not only delimited to the weight of coffee yield but take a broader perspective that comprises the farmer’s economy. This was done by conducting a review of previous research on the subject combined with a field study performed at six smallholding coffee farms with different levels of shade in Colombia from November to December 2014. The results of the field study serve as a site specific example and are discussed in relation to previous findings. Soil samples was taken at the farms and analysed for organic matter, soil moisture, respiration rate and acidity. The hypothesis was that the inclusion of trees in coffee cultivations can enhance the long term soil fertility when compared to monoculture systems. And also that agroforestry coffee can bring an increased safety for the farmer in terms of income, when compared to monoculture coffee. No general conclusions could be drawn based on the results from the field study; however the results show that a change from agroforestry management to monoculture management in coffee cultivations in Colombia can have a significant negative effect on soil respiration rate. Furthermore the study highlights the importance of taking into account the specific characteristics of the location and the management of the investigated farm when making conclusions about the effects of agroforestry on soil fertility. It is also concluded that long term studies, extending over at least a year, is necessary to fully see the effects of the cultivation practice on soil fertility.
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Appendix 1. Images showing the vegetation at the study sites.

Appendix 2. Images showing the soil at the study sites.
Introduction
Coffee is the 5th most widely traded commodity in the world today and a source of livelihood for millions of people (Bagyaraj, 2015; De Beenhouwer et al. 2014). It is estimated that 70% of the world’s coffee supply is produced by smallholder farmers (Caswell et al. 2012; Toledo et al. 2012). Coffee is also, together with cacao, the crop most commonly cultivated under shade trees (agroforestry) in order to cope with physiological stress (as drought and sun radiation) and erosion as well as to generate additional income for the farmer (Tscharntke et al. 2011; Pimentel et.al, 2011). However, today this agroforestry coffee management is increasingly transformed into industrial plantation with little or no shade using varieties that tolerates full sun and can be planted with higher density (Rodriguez et al. 2015). This conversion most often brings an intensified use of external input (i.e fertilizer and herbicides) and a reduction in biodiversity (Perfecto et al. 1996; Armbrecht et al. 2005; Armbrecht et al. 2007) as well as long term soil fertility (Ferreira et al. 2010). This goes in the opposite direction to the guidelines of the UN whose definition of sustainability is to provide the current needs of the present without compromising the future (United Nations).

Furthermore agroforestry has been highlighted by FAO (2013) as an important strategy to counteract hunger and environmental degradation worldwide.

A couple of reviews treating agroforestry and soil fertility in general have recently been written. The effect of trees on soil fertility in different types of agriculture system in Amazonia has been discussed in a review by Pincho et al. (2012). The effects of agroforestry on the microbiological processes in soil worldwide have been described by Ferreira Araujo et al. (2011). The short-term and long-term benefits of shade trees in coffee and cacao agroforestry have been reviewed by Tscharntke et.al (2011) who emphasize both the benefits for the farmer and for ecosystem conservation. The effect of tree-based agroecosystem on the abundance and diversity of Arbuscular mycorrhizal (AM) fungi is reported in a review by Bainard et al.(2010). A compilation of quantitative data from a vast number of researches concerning coffee agroforestry has been made by Van Oijen et al. (2010).

Agroforestry coffee systems has been shown to increase sequestration of carbon above- and below ground as well as favour biodiversity, when compared to monoculture systems. These areas are of great importance for the maintenance of ecosystems and future life on earth, but are not included in the scope of this thesis. For further reading on coffee agroforestry and biodiversity refers to the following articles: Potvin et al. 2005; Artilleri et al. 1992; Armbrecht

Purpose and structure of the study

The objective of this thesis is delimited to examine whether agroforestry favour soil fertility in coffee cultivation and how it stands in relation to the output of the system. The aspect of output will not only describe quantities of coffee yield but also take a broader perspective that includes the farmer’s economy.

The structure of the thesis consists of two parts. The first part is a literature study that begins with a broad introduction to the areas concerned and concludes with a summary of recent research in the area of Coffee agroforestry and soil fertility respectively yield and livelihood.

The second part consists of a presentation of a field study conducted at coffee cultivations with different farming practices in Colombia during November-December 2014. The fieldwork was supported by a Minor field study (MFS) scholarship and was performed by Ida Ekqvist and Josef Ingvarsson. The results from this fieldwork will be presented in two thesis, of which this is one, focusing at different areas and different parts of the result. For further reading about sustainability in coffee farming systems in Colombia refers to Ingvarsson (2015).

The review was carried through by conducting a systematic literature search based on a number of keywords in different combinations. The search results are compiled in a matrix to and to get a quantitative overview of the current literature on the subject. The databases used were mainly Web of Science and in a smaller extent Springer Link. Google scholar where also used in a few occasions when an article that were deemed interesting were not available in the earlier-mentioned databases.

Criteria of inclusion for articles

- The article has to be peer reviewed and published in a scientific journal.
- The article has to be fully accessible without charge.
- The article has to be written in English or Swedish.
**Agroforestry**

Agroforestry is an integrated farming system where trees, shrubs, field crops and/or animal production are combined on the same piece of land at the same time. Such system takes advantage of the productive and protective value of trees and the benefits of diversity in the agroecosystem. The practice is not a new invention; farmers have long practiced intercropping of agricultural crops with trees as a way to satisfy their need for food, wood products, fodder and economic stability (Gliessman, 2007). Apart from the useful products derived from trees, such as fruits and timber, the inclusion of trees can work conservative and protective of their limited land resources (Gliessman, 2007).

Agroforestry as a farming method has been shown to have a great potential for combining a high productivity with conservation of natural resources and enhanced livelihoods for farmers (Björklund et al, 2012). Furthermore, farming system with trees are shown to be more labour- and energy efficient, to have a positive effect on ecosystem services, to be able to lessen the need of pesticides and also to be efficient in terms of water use (Jose, 2009).

**Coffee:**

Coffee is a perennial and woody plant (Bagyaraj, 2015) that origins from Southwest of Ethiopia, where it grows as a natural understory shrub in the rainforest (De Beenhouwer, 2014). It was introduced into the Americas in 1723 (Perfecto et.al, 1996). Since then coffee has reached a substantial importance globally and around 2, 5 billion cups of coffee are consumed every day, which makes it the most popular drink worldwide (Notaro de Alcantara, 2013; Bagayaraj, 2015).

The two main species of coffee cultivated today is Arabica coffee, *Coffea arabica L* and Robusta Coffee, *Coffea canephora* (Bagyaraj et al. 2015). They differ in terms of taste and management requirement. Robusta seems to be more resistant to abiotic stress such as drought, intensive rainfall and solar radiation and can be grown in lowland forests (Filipe dos Santos et al. 2015). Arabica on the other hand is considered to be of higher quality in terms of taste (IOC, 2013). Arabica, consisting of a variety of cultivars, is the most commercial
important of the two species, representing 60-80% of the coffee production worldwide. (De Beenhouwer et al. 2014; Bagyaraj et al. 2015, ICO, 2013). The coffee produced in Latin America and Central America are mainly Arabica coffee (Van Oijen et al. 2010; ICO, 2013). Since this thesis will focus on this region it will mainly treat cultivation of Arabica coffee.

**Coffee Management**

Coffee is grown in more than 50 countries and even though these countries have some cultivation practices in common they differ slightly in their management and technologies due to their specific geographical positions and altitude (ICO, 2013). Traditionally the coffee plant is grown under the shade of canopies. This cultivation practice will henceforth be referred to as either agroforestry or shade coffee.

The coffee plant requires a balanced temperature since it tolerates no frost and neither overly high temperature. The plant also requires conditions with plenty of water available, but needs periods of rain followed by dry periods to produce well (Van Oijen et al. 2015). The optimum annual mean temperatures for coffee cultivation are around 18-23 °C (Da Matta et al. 2006). Exposure to temperatures above the optimal cause disturbance in photosynthesis and often have a negative effect on bean quality and size (Filipe dos Santos et al. 2015). The optimum annual rainfall range is 1200-1800 mm. The coffee plant is sensitive to strong winds and high air humidity and is adapted to grow in the highland forests of Ethiopia at altitudes ranging from 1600 to 2800 m (Da Matta et al. 2006). It furthermore seems to be well adapted to acid soils conditions and is commonly cultivated in soils with a pH ranging from 4-6 (Vaast et al. 2008). The coffee plant is highly dependent on mycorrhiza for its nutrient supply (Osorio et al. 2007). Moreover, the plant is often grown on poor soils in the tropics where the supply of nutrients, including phosphorous, is scarce.

**Challenges in coffee production**

**Climate changes**

The global climate is likely to change at least 1,5°C within the 21st century and changes in extreme weather event has been observed over the past 50 years (IPCC, 2014). Coffee plant,
in particular *C. arabica*, has been proven to be highly sensitive to predicted future climate changes. It has been suggested that climate change will make a substantial part of the current coffee cultivation areas unsuitable for coffee production in the future. And that future climate change most likely will drive the need for fundamental changes in coffee production system on farms (Bunn et al. 2014; Lin, 2009)

**Coffee Crisis and modernization**

Coffee farmers have been subjected to a drastic drop in market prices for coffee the last decades. This “coffee crisis” began in the 90’s and was caused by an overproduction of coffee (Ponette-Gonzáles, 2007). The international Coffee Organization (ICO) introduced an agreement 1963 (The International Coffee Agreement) that implied a regulation of the market supply and demand by quotas. These quotas were removed by 1986 which led to a widespread over production that caused the market price drops (Álvarez, 2010). This led to a situation where the traditional coffee cultivation with shade often was unable to generate enough income for the household of the farmers. The coffee crisis obliged many farmers to minimize their monetary expenditures (e.g. purchase of fertilizer and pesticides) and to seek extra income outside the farm or sometimes to abandon the land and seek other way of making a living (Álvarez, 2010). It was and still is common that farmers convert a traditional coffee cropping system to monoculture system or switch to another crop in hope of a more yield-intensive and cash-generating crop production to cope with this situation (Ponette-Gonzáles, 2007).

There are other examples of farmers dealing with the effects of the coffee crisis by organizing and using their social capital to carry through alternative survival strategies. By organizing at different levels coffee farmers have been able to add value to their product and enter markets of premium coffee (e.g. organic or biodiversity coffee) which makes it possible to bargain for fair prices and thereby get a protection from the drastic price drops at the free market (Altieri & Toledo, 2011). There are plenty of peasant movements and cooperative organizations at different levels present in Latin America. These movements represent a significant resistance against the agriculture industrialization and neoliberal polices and often promote agroforestry coffee system as a way to self-sufficiency. Within these movements there is a call for agrarian reforms so that small scale farmers can produce food for their own communities and countries (Toledo & Moguel, 2012; Altieri & Toledo, 2011).
The social and cultural aspects of peasantry in different locations in Latin America are crucial to fully comprehend the development and complexity of coffee farming in this area, but will not be described further in this thesis due to limitation in scope and extent. For further reading refers to Altieri & Toledo (2011) who provide an overview of the agroecological revolution happening in Latin America and describe various grass root initiative made by peasant movements.

**Diseases**

A particularly extensive epidemic of coffee rust affected Latin America during 2008-2013 (Avelino, 2015). It is suggested that the low coffee prices in combination with an increased cost of inputs (fertilizer and pesticides) led to non-optimal management of coffee cultivations which in turn increased the vulnerability to pest and diseases (ibid.). Coffee rust is caused by a fungus that attacks the leaves and branches of coffee bush. The disease can lead to a significantly reduced yield. In El Salvador the coffee rust caused a decline in production by 54% from one year to another (Avelino et. al, 2015). Strong action has been taken by government authorities and coffee organizations in Latin American to fight the epidemic (Pinzon, 2012). These actions often involve a shift from shade coffee system to monoculture with new coffee varieties resistance to coffee rust (Avelino, 2015).

Another serious pest that has widely affected the coffee production in Latin America is The Coffee Berry Borer. This insect is considered to be the most important pest in coffee plantations (Vega et al. 2009).

**Soil Degradation**

Soil degradation is an extensive problem that is caused by bad soil management and is estimated to affect 38% of the world cropping land (Leakey, 2014). Indicators of soil degradation include among other things a loss of organic matter, porosity, water infiltration, structure, permeability and microbial activity. This microbial activity function as the main supplier of nutrients to the soil as the microorganisms decompose organic matter derived from the vegetation (Gliessman, 2007). In the process of decomposition some of the residues of the microbial activity are converted into more stable compounds called humified organic matter. These compounds are very resistant to further breakdown and represent 90-95% of the soil’s
total organic matter content (Gliessman, 2007; Eriksson, 2011). The humified organic matter gives the soil a dark colour which is a useful indicator when assessing the properties of a soil. These processes to form soil organic matter are of extra importance in tropical soils, where the warm and humid climate has caused an intense chemical weathering on the parent material which results in soils that are deep, leached and scarce in plant nutrients (Pincho et al. 2012; Gliessman, 2007). These types of soils often have a very rich diversity and high biomass of microorganisms that play an important role in providing nutrients through decomposition of organic matter. Thus, to continuously remove organic matter from the surface of these soils will make them depleted of nutrients in a short time (Pincho, 2012). One traditional way to cope with this problem is to leave the land to fallow for a period to regenerate the soil fertility, often combined with preparing the new proposed cultivation area by burning. This can cause loss in soil fertility depending on performance (Gliessman, 2007) Agroforestry may be a better alternative to this method as it not only enhance soil fertility but also control erosion (León & Osorio, 2014).

Soil conservation, that is one of the most urgent areas of environmental protection, is especially important in steep highlands area where coffee often is grown. These tropical mountain areas is very vulnerable for soil erosion due to steep slopes and heavy rainfalls (Verbist et al. 2009).

A considerable part of the soil degradation takes part in developing countries, where economic weak farmers must rely on a small piece of land for their livelihood (Leon & Osorio, 2014). It is often a desire of security and a hope for higher yield and better livelihoods that often drives the use of unsustainable soil management in this case (Leakey, 2014). The expected outcome from agriculture technologies such as new more durable and high-yielding crop varieties is limited by the lack of ability to purchase the essential, and often costly, inputs for the agriculture system. This leads to declining yields and a depleted soil fertility which leads to more poverty, in a downward spiral (ibid.). It has to be mentioned also that this situation is strongly influenced by socioeconomic factors as local governance and access to markets as well as natural disaster, conflicts, war and not the least: international policies and trade agreement (Leakey, 2014).
The influence of Trees on Soil fertility in coffee farming systems

**Soil organic matter and microbial life**

A large number of studies have been made to investigate the effect of agroforestry on soil organic matter and microbial activity in coffee cultivations. Trees can enhance the organic matter content in cultivations due to its litter production and thereby favour the microbial life and diversity (Ferreira et al., 2011; Zake et al., 2015; Bagaray et al., 2015). However it is evident that this correlation cannot always be found in coffee agroforestry system since the content of organic matter and microbial life also depends on other factors, such as fertilization practices and the composition of tree species in the system (Leon & Osorio, 2014; De Souza et al., 2011b; Bae et al. 2012; Bagaray et al. 2015). A higher number of tree species has been shown to bring benefits such as faster decomposition and enhanced nutrient cycling due to the high diversity of litter qualities (Wang et al. 2014). The leguminous tree *Erythrina poepiggiana* has been pointed out to be particularly good at increasing the soil organic matter (Leon et al. 2006). Furthermore agroforestry has been found to enhance the content of easy degradable components in the organic matter (Barros Marinho, 2014).

The inclusion of trees in a system also seems to affect the activity per unit microbial biomass of the microbial communities. A study that showed no significant different in basal respiration between monoculture and polyculture coffee showed a higher respiration to biomass ratio i.e a higher activity (metabolic quotient) per unit microbial biomass, in the polyculture system compared to the monoculture (Pimentel et al. 2011). Other findings show how deforestation in favour of crop cultivation not only cause a reduction in microbial biomass and respiration rate (Bae et al. 2012) but also a change in microbial community towards microbial life with a higher catabolic activity, and thus higher C turnover rate, in the cultivated fields (Raisei et al. 2014). These results indicate the influence of trees on microbial activity. The respiration in agroforestry coffee has shown to be similar to that of a native forest during the wet season, but this relationship was not found during dry season when the forest had significantly higher respiration rate (Bae et al. 2012). The authors furthermore argues that the respiration rate seems to be affected by soil moisture in areas particularly exposed to water stress, i.e drought or too much rain (ibid.). The soil moisture in agroforestry coffee system has been found to be higher compared to conventional coffee system (Guimaraes et al. 2014; Lin, 2009b). Thus,
manipulation of soil moisture by inclusion of trees may be a useful strategy to enhance the respiration rate in coffee cultivations in dry areas.

**Nutrient cycling**

Trees have been shown to favour soil fertility through enhanced nutrient cycling since their roots go deep down in the soil and reach nutrients that may not be accessible to the coffee plants (Pincho et al. 2012). The roots of coffee varieties growing in monocultures under full sun condition have certainly proved to have deeper roots than shade coffee plants, probably due to less litter derived nutrients in the superficial soil layer in monoculture coffee (Da Matta et al. 2007). However, this can be considered to be out weight by the larger association with mycorrhiza in agroforestry system (Shukla et al. 2012). The symbiosis between plants and the mycorrhiza fungi is one of the most ecological and economical important interactions taking place below ground since it contribute to the plant’s nutrient supply which is of particularly importance concerning the availability of phosphorous (Eriksson et al. 2011). The fungal hyphae reaches deep into the soil and has access to nutrients that are beyond the reach of plant roots and also provide the plant with a protection against uptake of toxic metals and pathogens as well as enhanced water uptake (ibid.).

Monoculture coffee cultivations exhibit more mycorrhiza spores in the superficial soil layer than agroforestry. But agroforestry on the other hand show more mycorrhiza spores at a deeper soil layer (Bagyaraj et al. 2015; Cardoso et al. 2003). This may be explained by the higher quantity of root mass in the top 30 cm soil layer in agroforestry that probably reduced the need of mycorrhiza for nutrient uptake in that soil layer (Cardoso et al. 2003). It has also been highlighted that mycorrhiza colonisation in coffee cultivations benefits from the use of organic fertilizer (Hernando & Sieverding, 2013) and a diverse mix of tree species in the agroecosystem (Bagyaraj et al. 2015). The diversity of mycorrhiza seems to be greatly favoured in forest conditions compared to cultivated land (de Beenhouwer et al. 2014). This may indicate that the diversity of trees and species affect the diversity of mycorrhiza species. There are findings showing that agroforestry favour a higher fungi-population (Bagyaraj et al. 2015), but it has also been concluded that mycorrhiza colonization not always benefits from agroforestry management, probably due to several factors, including tree diversity and choice of tree species (Bainard et al.,2010). However there are other studies showing that mycorrhiza
do not to have any preference for specific tree species in agroforestry system (Shukla et al. 2012).

Regarding nutrients, P is shown to be a limiting nutrient in many coffee agroecosystems (Notaro et al. 2013; Zake et al. 2015). The contribution of litter from trees is suggested to have a considerable positive effect on P cycling and hence the available P content in soil (Notaro et al. 2013; Baros Marinho et al. 2014; Da Silva Matos et al. 2011). This can be explained by the higher degree of root-mycorrhiza symbiosis at a deep soil level when trees are present (Cardoso et al. 2003). However, whether the P cycling increases in a coffee agroforestry system or not seems to depend on the specific characteristics of that system (Xavier et al. 2010). As an example the P content has been found to be higher in coffee under organic management than conventional (Tully et al. 2013a).

The nutrition status in soil can be further improved by inclusion of legume trees (da Silva Matos et al. 2011, Tully et al. 2013b). This is due to a symbiosis with the *Rhizobium* bacteria that provide the plant with nitrogen taken from the atmosphere (Gliessman, 2007; Tscharntke et al. 2007; Leakey et al. 2014). The selection of tree species and thereby the quality of litter have influence on N mineralization dynamics in the soil. Greater N content in litter favour the microbial population and diversity (López Rodríguez et al. 2015; Bae et al. 2012), since microbes need N to reproduce, which in turn increase N cycling (Eriksson et al. 2011). The mineralization of the N content in litter is slower in shaded coffee than in sun coffee (da Silva; Lopez Rodriguez) while the mineralization of the N content in soil is faster in shaded coffee than sun coffee (López Rodríguez et al. 2015). These dynamics of N-mineralization in agroforestry systems is suggested to provide a sustainable N cycling (ibid.) as it probably reduces N leaching. This is in accordance with Tully et al. (2012) findings that N losses decrease linearly with increasing tree density in coffee cultivations. There are plenty of studies showing that mechanisms that prevent leaching of nutrients exist in coffee agroforestry system (Tully at al. 2012; Verbist et al. 2009). Furthermore *Erythrina poepiggiana* has been shown not to be particularly competitive against coffee plants in terms of available nutrients (Mora & Beer, 2012).

Furthermore agroforestry has been found to increase the populations of macrofauna in soil (Pimentel et al. 2011; Leon et al. 2006) which play an important role in the soil structure formation, nutrient recycling and degradation of organic matter (Eriksson et al. 2011).
**Soil structure and acidity**

Agroforestry coffee has been found to have a lower resistance to penetration, i.e. less soil compaction, compared to coffee systems without trees Guimaraes et al. (2014). In addition these systems featured higher carbon content in the aggregates, when compared to conventional coffee cultivations (Guimaraes et al. 2014). These findings are expected since organic matter serve as one of the main factors that promote aggregate formation (Eriksson et al.). A loss in aggregation may have negative effects on microbial biomass, among other things (Raiesei & Behesti, 2014).

Agroforestry has been shown to reduce acidity in soils (Barros Marinho et al. 2014), however the selection of specific tree species may affect the changes in pH. Leguminous trees have been shown two contribute to a lower pH when compared to other species (Tully et al. 2103). The use of mineral nitrogen fertilizer is also shown to increase soil acidity (ibid.). Acidity in soils is known to negatively affect the density of soil bacteria (Eriksson et al. 2011) and cations exchange capacity (Tully et al. 2013). Furthermore a soil very high or low in pH negatively affects the plant’s uptake of nutrients (Gliessman, 2007). The concentration of H\(^+\) increases as a result of the loss of bases from the soil and through the production of H\(^+\) by the plant roots when absorbing nutrient cations and also by microorganisms. A reduction in bases takes place in the soil due to leaching of nutrients, harvest of biomass and the uptake of nutrients ions by the plant. There are several buffer systems present in the soil that determines the pace of the acidification. The most important buffering processes include weathering of minerals and acid-base reactions of weak organic acid (Gliessman, 2007; Eriksson et al. 2011).

It has been pointed out that there is a need for more long term studies of coffee agroforestry to get enough data to make useful analyses of the system (Van Oijen et al. 2010). To fully comprehend the development throughout the whole life cycle of the plant studies need to be conducted during a period of several years.
The influence of trees on yield and economic viability of farms

Effects on yield

A number of studies have examined the relationship between yield and coffee agroforestry/shade coffee the past 15 year. When it comes to yield, there are several studies showing both the benefits and disadvantages of tree inclusion in coffee cultivations. Dissemination of finding may depend on the different objective taken by the authors. Monoculture coffee with high plant density has been shown to possess a significantly higher production capacity in terms of coffee yield per unit area (Da Matta, 2008, Lopez-Rodriguez et al. 2015). Three possible reasons for this is that shade management cause: lower carbon assimilation in the tree, a decreased growth of flower buds in favour of vegetative growth and fewer nods formed per branch Da Matta (2007). Other studies have found a relationship between high degree of shade and low yield (Meylan et al. 2013) but there are also indications that shade management keeps a more stable (long term) production over time (Meylan et al. 2013; De Souza et al. 2012) and that organic agroforestry system may well feature equal or higher yield than conventional sun coffee systems if enough organic input and a proper farm management are performed (Leon et al. 2006). In a review aiming at making a quantitative account for the existing scientific data on Coffee Agroforestry Van Oijen et al. (2010) highlight the need for more long-term experiments to fully get a picture of development of yields over years.

The relationship between yield and shade are not linearly. How the shade affects the yield highly depends on the abiotic factors present on the site where the coffee is cultivated (Meylan et al. 2013). Thus, to get a good yield there has to be an appropriate shade level well adapted to the site specific conditions (Lopez-Rodriguez et al. 2015; Da Matta et al. 2007; Meylan et al., 2013; De Souza et al. 2012). As an example shade density should be kept low in west facing slopes due to the higher humidity and lesser availability of solar radiation (Meylan et al., 2013). There exist a wide diversity in farming strategies and selection of trees in coffee agroforestry as well as sun coffee and this must be taken into account as it strongly affects the productivity and profitability of the system. The same authors also note that
agroforestry can perform as high yield as sun coffee, and furthermore with a better quality which can give higher cash value for the farmer when selling the beans. However, whether shade has positive effects on the taste quality of beans is not agreed upon since studies show different results in the issue. Bosselmann et al. (2008) found no significant relation between shade and sensory properties while Läderach et al. (2010) found the level of shade to influence bean quality, but in a very site specific way.

Soil moisture in agroforestry system has been shown to be considerably higher than in full sun system (Guimaraes et al. 2014). Fruit weight, fruit growth and reduced fruit drop correlate positively with soil moisture and these factors can thereby be effectively regulated by the use of shade trees. Fruit growth has furthermore been found significantly positively affected by the level of solar radiation, humidity and temperature present in a coffee system with high level of shade (80%) (Lin, 2009). However, since this study was performed with only one replication of each treatment and on an east facing slope these results may not be generally applicable.

**Increased resilience on farm**

The inclusion of trees in coffee cropping system contribute to a more stable microclimate and can serve as a good way for farmers to protect themselves against future climate change (Lin 2009; Lin, 2006; De Souza, 2011b; Poveda et al.2001) that is predicted to lead to a more varied climate and a higher frequency of extreme weather events (IPPC, 2014). As an example the most diversified coffee cultivations in a coffee growing region in Mexico suffered less damage by a hurricane compared to the less biodiversity rich coffee cultivations in the area (Altieri and Toledo, 2011). Moreover, a cultivation rich in biodiversity most likely features more functions carried out by ecosystem services, such as nutrient cycling, pest predation, nitrogen fixation, than a system with less diversity (Toledo & Moguel, 2012, Perfecto et al. 1996; Leakey, 2014).

This may imply a decreased cost for fertilizer and other external farm input needed to carry out these functions in a less diverse system (Perfecto et al., 2007). Farming system with high diversity seems to lessen the vulnerability to attacks from pest and fungi when compared to a typical monoculture system, which may have an effect on the productivity (Da Matta, 2009; Leakey, 2014, Tscharntke et al. 2011; Armbrecht et al. 2007; Armbrecht 2005; Perfect et al.
Furthermore, a coffee farming system rich in biodiversity opens up for the ability to get the coffee certified as ‘biodiversity-friendly’ which adds value for the farmer when selling the coffee on the highly fluctuating market (José & Gobbi, 1999).

The coffee growing areas often constitute habitats particularly rich in biodiversity. These areas are therefore of major concern in terms of conservation measures (Perfect et al. 2006). Another management strategy that has shown to be successful in order for smallholder to obtain a high coffee yield simultaneously as conserving the biodiversity is a cropping system called Integrated Open Canopy (IOC). This involves culturing coffee with little or no shade while conserving an area of native forest equal in size to the cultivated area. The result is regularly occurring corridors of forests between fields of coffee (Chandler et al. 2012).

The diversity of products produced by a traditional shade coffee system, in particular if it is a combination of subsistence- and cash crops, constitutes a broader base of livelihood for the farmer and hence provide a higher food safety and stability than if the farmer has to rely on one cash-crop for subsistence (Tscharntke et al. 2011; Toledo & Moguel, 2012; Leakey, 2014). A study that put focus on the overall economical productivity of different coffee system (De Souza et al. 2011) found agroforestry coffee management to be significantly more productive (43%) in terms of total production value than full sun coffee, when measured over a period of 12 years. Similar conclusions are made by Altieri and Toledo (2011) who show that the productivity of small and diverse family farms are higher than that of large farms if the total production is taken into account rather than the yield from a single crop.

**Introduction to the case study at coffee farms in Colombia**

This field study was carried out at six smallholding coffee farms in Colombia in November and December 2014 and was supported by SIDA through a Minor Field Study (MFS) scholarship. The purpose of the study was to examine how agroforestry affects soil fertility in coffee cultivations when compared to monoculture. The main hypothesis tested was that coffee cultivation under agroforestry management shows higher microbial activity (i.e. respiration), organic matter content and soil moisture. Furthermore it was hypothesized that the respiration rate increases in relation to the organic matter content in the soil.
Background

**Coffee production in Colombia**

Colombia is the fourth largest producer of Coffee in the world, preceeded only by Brasil, Vietnam and Indonesia (IOC, 2013). Agriculture has traditionally constituted an important base in Colombian Economy, but has seen a steady decline the past decades and today it accounts for around 6% of BNP. The land area used for agriculture in Colombia is below 2% and has been halved in a period of 20 year (1988-2008) (The country guide, 2014). More than half of the land area in Colombia is forests and the arable land is often uneven distributed. The FARC guerrilla has chased away many farmers from their land which has led to a situation where 7, 5% of the total population in Colombia are displace people. Without access to their land these people are forced into the cities to earn a living, which partly explain the decline in agriculture (Álvarez, 2010). The question of land reforms has long been an issue in the country and a source of conflict between the government and the guerrilla (The country guide, 2014). Cultivation of illegal crops occupy no more than 200 000 ha land but constitute a considerable part of the total value of agriculture production if included in this category (Álvarez, 2010).

Colombia produces solely the variety *Coffea arabica* (Álvarez, 2010), and this crop is the agriculture commodity that generates the highest total export value in Colombia, while banana stands for the largest export quantity (Figur 1) (FAOSAT, 2013). There is over half a million coffee farms in the country that employs a third of the country’s farmer. Most of these farmers are smallholders and 96% of the farms are less than 5 ha (FEDERCAFE, 2013).
Colombia consists of 32 departments with a great variety in climate and agriculture conditions (The Country guide). The region is occasionally exposed to the weather phenomenon El Niño and La Niña which means alternately occurrence of periods that are wetter respectively drier than normal (Poveda et al. 2001). The main Coffee growing area is located in the Andean area (Millennium Ecosystem Assessment, 2005) which is located between three mountain ranges and covers an area of 305 000 km² (Sinclair et al.). The most important economic and urban centres in the country are situated here as well as 70% of the Colombian population (ibid.). Coffee is grown at hillsides in this region at an elevation ranging from 1000-2000 meter (Millennium Ecosystem Assessment, 2005) in a soil which is often characterized by volcanic ash (Barrios et al. 2005). The traditional agriculture in this region is characterized by the use of fallow to restore the soil fertility which involves burning new land areas for cultivation (ibid.).

The coffee rust outbreak in the 2010’s struck hard against the coffee production in Colombia and caused a considerably lower production in the country (see Figure 2) (Álvarez, 2010; FAOSTAT). From 2008 to 2011 the national coffee production was reduced by 31% (Avelino et al. 2015). The government of Colombia and the Colombian Coffee Growers Federation has put big effort in an extensive renovating programme where farmers get financial and advisory support to carry on replacement of traditional coffee varieties by a newly developed variety named Castillo. This variety can advantageously be cultivated in full sun and is resistant to coffee rust. Since 2009 a large part of the fields planted with traditional coffee varieties have been replaced by Castillo (Avelino et al. 2015). About two-thirds of the coffee in Colombia is currently grown in sun exposed monoculture (Da Matta et al. 2007) and more than 60% of the

![Export value of food and agricultural commodities in Colombia](image)

**Figure 1.** Illustrate the distribution of the ten agricultural commodities with highest export value in Colombia (Data source: FAOSTAT).
coffee cultivations consist of resistant varieties. This is likely the reason for the steady recovery in productivity seen in Colombia the past year (ICO 2013).

![Coffee yield in Colombia](image)

**Figure 2.** Data on yield per hectare and year. The large decline 2009 show the result of the coffee rust outbreak (Data source: FAOSTAT).

**Coffee production in Tolima**

Tolima is the third largest producing department of coffee in the country with a share of 12% of the national coffee production (FEDERCAFE, 2013). Coffee is by far the most commonly cultivated perennial crop in Tolima and is also the individual agricultural crop that occupies the largest cultivation area in the department (Gobernación del Tolima, 2013). The topography in Tolima is very uneven, ranging from snow-capped mountain peaks with an altitude of over 5000 meters and down to valleys situated 400 meters above sea level (Google maps). Coffee is cultivated in 38 of the 47 municipalities of the department by 61537 families with a mean area of 1, 63 ha on each farms. The vast majority of these farms have partly or fully abandoned traditionally coffee farming in favour of more technical developed farms in terms of input, varieties and management, see Figure 3 (FEDERCAFE, 2014).
Materials and methods

Study site

The study was carried out at six small-scale coffee farms close to Ibague, the principal city in the department of Tolima (see figure 5), from November to December 2014. The climate of Ibague is classified as a slightly cooler version of the tropical rainforest climate, in accordance with the climate classification system of Köppen-Geiger (Peel et al. 2007). The average daily temperature is around 24°C and is almost constant over the year. The annual precipitation in the region is approximately 1700 mm and has a bimodal distribution with the rainiest periods in October-November and April-May and the driest in January and July. However there is no real dry season since the average monthly precipitation is never less than 70 mm. July and August features the lowest humidity (see figure 4) (Instituto de Hidrología Meterología y Estudios Ambientales, 1999). There are two active volcanoes in the area and the soils are largely composed of metamorphic rock mixed with volcanic ash.
The farms were selected with help of staff at Tolima University using following criteria:

- The farm should be located at the same altitude ( +/- 200 m)
- The current cropping system at the site of investigation must have been in use for at least 10 years.
- The coffee field of investigation must have approximately the same type of soil and slope.
- Half of the chosen coffee fields should be managed as monoculture, i.e without shade trees, and the other half should be managed with shade trees.

Four farms were selected. Two of these farms were separated into two coffee fields because one part of the farm was managed as a monoculture and the other was managed with shade trees, giving a total of six fields. The management practices, such as fertilizer, pesticides and number of shade trees in the cultivation, varied between all fields and are presented in Table 3. Images of the fields can be seen in Appendix 1.

The fieldwork was conducted between 21 and 29 November 2014. Farm 1 & 2 are located about 10 km northwest of Ibague while farm 3 & 4 are located close to each other around 15 km south west of the city. The altitude of the farms ranged from 1590 to 1870 meters and all the fields were characterized by very steep slopes (>50 %) with farms 2 being steepest followed by farm 1. A particularly large number of stones were encountered in the field at
farm 3 and slightly less at farm 1, compared to the other two farms. The colour and structure of the soil differed. For images and descriptions of the soil see Appendix 2.

Farm 1 was renovated 3 years ago with the roja-resistant variety Castilla. The agroforestry field at farm 1 is a small field with shade trees that was kept from renovation and the area has not been managed actively since that. This agroforestry field (1AF) was overgrown with lots of bananas and large trees, it resembled a forest. The trees grew close to each other and the shade level was high. The coffee bushes did not appear to be in optimum condition. The monoculture field (1MC) was previously coffee and banana agroforestry for at least 30 years. The fields at farm 2 were situated at a north facing, very steep slope. The agroforestry field (2AF) was located higher up at the hillside, directly above the monoculture field, and did not have very much trees. The trees were mainly concentrated to the borders of the field and a few trees in the middle of the field, with approximately 10-15 meters in between. The monoculture field (2MC) had some banana trees, approximately 10-15 m apart from each other. Both fields at farm 2 had same pest and fertilizing management. Farm 3 was not very intensively managed at the time because the farmer had recently taken over the management of the farm from the previous farmer. Farm 4 was intensively managed.

**Figure 5.** (Left) Map of Colombia with sampling area (Ibagué) marked with a red dot. (Right) Map of the the sampling areas showing the terrain and positions of farms (Source: www.google.com/maps)
All the farms was managed by smallholding farmers and the size of the fields ranged between 0,9 to 3,5 ha. Most of the fields had been under current management practice during at least 15 years except from two of the monoculture fields that were younger.

Figure 6. (Left) The steep slope at the agroforestry field at farm 1. (Right) Coffee landscape in the area of farm1 and farm 2 (Photos: J.Ingvarsson & I.Ekqvist).
<table>
<thead>
<tr>
<th>Sites</th>
<th>Farm 1, AF (F1AC)</th>
<th>Farm 1, MC</th>
<th>Farm 2, AF</th>
<th>Farm 2, MC</th>
<th>Farm 3, AF</th>
<th>Farm 4, MC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>4.49041, -75.28343</td>
<td>4.49041, -75.28343</td>
<td>4.48551, -75.27452</td>
<td>4.48551, -75.27452</td>
<td>4.40224, -75.33365</td>
<td>4.39977, -75.33373</td>
</tr>
<tr>
<td>Altitude</td>
<td>1590 m asl</td>
<td>1590 m asl</td>
<td>1782 m asl</td>
<td>1782 m asl</td>
<td>1740 m asl</td>
<td>1870 m asl</td>
</tr>
<tr>
<td>Area</td>
<td>0.9 ha</td>
<td>1.5 ha</td>
<td>3.0 ha</td>
<td>5.0 ha</td>
<td>2.0 ha</td>
<td>3.5 ha</td>
</tr>
<tr>
<td>Age of the field</td>
<td>older than 15 years</td>
<td>3 years as monoculture. Previously banana &amp; coffee for 30 years.</td>
<td>Older than 15 years</td>
<td>Older than 15 years</td>
<td>older than 50 years. Has been an avocado plantation before 7 years with coffee. Before that sugarcane.</td>
<td></td>
</tr>
<tr>
<td>Clay content in soil</td>
<td>19.2 %</td>
<td>13.22 %</td>
<td>7.2 %</td>
<td>7.2 %</td>
<td>13.2 %</td>
<td>13.2 %</td>
</tr>
<tr>
<td>Slope</td>
<td>south facing slope, very steep</td>
<td>south facing slope, very steep</td>
<td>north facing slope, extremely steep</td>
<td>north facing slope, extremely steep</td>
<td>north facing slope, very steep</td>
<td>north facing slope, very steep</td>
</tr>
<tr>
<td>Fertilizer</td>
<td>no</td>
<td>every 4 months</td>
<td>chemical fertilizer every 4 months. 80 gram per plant npk+ zink</td>
<td>chemical fertilizer every 4 months. 80 gram per plant npk+ zink</td>
<td>no</td>
<td>every 6 months. NPK=magnesium+ulsphur. 100 gram/plant</td>
</tr>
<tr>
<td>Compost</td>
<td>no</td>
<td>Coffee shells 3 years ago. Sometimes compost.</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>Pesticides, herbicides and fungicides</td>
<td>no</td>
<td>no</td>
<td>Herbicides 6 months ago. Pesticides one time last year. Apply fungicides every 6 month</td>
<td>Herbicides 6 months ago. Pesticides one time last year. Apply fungicides every 6 months</td>
<td>no</td>
<td>Fungicide was used once, 6 years ago, when the coffee plants were small.</td>
</tr>
<tr>
<td>Problem with pests</td>
<td>Roya (20%)</td>
<td>The sickness &quot;palomilla&quot;</td>
<td>Roya</td>
<td>Roya</td>
<td>No Roya, but a disease called macana.</td>
<td>Roya, only in caturra</td>
</tr>
<tr>
<td>Coffee plants</td>
<td>1-1,5 m</td>
<td>1-1,5 m</td>
<td>1,2 m (planted in triangles)</td>
<td>1,2 m (planted in triangles)</td>
<td>2 m</td>
<td>1,3 m between the trunks, 1,7 m between lines.</td>
</tr>
<tr>
<td>Age</td>
<td>older than 15 years</td>
<td>10 years</td>
<td>10 years</td>
<td>more than 15 years</td>
<td>7 years</td>
<td></td>
</tr>
<tr>
<td>Coffee production per year</td>
<td>no data</td>
<td>no data</td>
<td>1875kg (dry weight)/ha</td>
<td>1750kg/ha</td>
<td>250 kg/ha</td>
<td>1785kg/ha (wet weight)</td>
</tr>
<tr>
<td>Varieties</td>
<td>Caturra</td>
<td>Castilla</td>
<td>Caturra, Tipica &amp; Bourbon</td>
<td>Caturra &amp; Castilla</td>
<td>Tipica &amp; Caturra</td>
<td>Castilla &amp; Caturra</td>
</tr>
<tr>
<td>Main Species</td>
<td>Advocado, banana, citric fruits, timber and leguminous trees</td>
<td>No trees</td>
<td>Bananas, cedawood, one leguminous tree: chachafudo, timber</td>
<td>Cedarwood, advocado (the most common tree), banana, forforillo, timber (3 different species), leguminous tree, orange, lemon.</td>
<td>No trees except from some bananas. Thats not for the shade but for the extra income.</td>
<td></td>
</tr>
<tr>
<td>How old are the trees</td>
<td>Older than 15 years</td>
<td>Older than 12 years. (Banana: 8 years)</td>
<td>Older than 20 years</td>
<td>7 years (banana)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Distance between tree trunks</td>
<td>Bananas &amp; Advocado: 3-5 m 20-Lager trees: 30 m</td>
<td>20 meter</td>
<td>Avocado: 30 meters</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Views concerning disadvantages of having trees in the plantation</td>
<td>no</td>
<td>Lower yield since the trees compete with the coffee bushes.</td>
<td>Production goes down during rain season due to insufficient heat.</td>
<td>In colder climate the shade reduces the yield. Castilla is designed for sunexposure.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Experienced benefits from having trees in the plantation</td>
<td>Better quality of soil. The shade system doesn’t demand so much work. More income.</td>
<td>Bigger coffee beans. Better quality of the dried coffee bean. Less sicknesses and plague. Better physical apperance</td>
<td>Increased incomes from other crops (bananas) and increased organic material</td>
<td>Income from other sources and better microclimate.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Field work

The site of investigation on each farm was selected in dialogue with the farmer, who was present during the field study, to find an area that was representative to the field. GPS coordinates including altitude was determined for the selected site. A general inventory of the vegetation was made. To obtain information of the characteristics of the farms a semi structured interview was carried out with the farmer and conducted by Jaqueline Chica Lobo, staff at Tolima University. The question used in this thesis was concerning yield, history of the farm and management practices such as use of fertilizer, pesticides and shade trees and the answers are presented in Table 1.

Soil Sampling

All samples was taken at three points along a transect (approx. 25 meters) at the chosen site. The transect was place so that the sampling plots was at least 10 meters from the border of the plantation. The transect followed the slope in a diagonal, where point nr.1 was at the lowest altitude and point nr.3 at the highest. At each point three soil samples was taken, with 50-100 cm in between, and then mixed to form one sample. The samples at the first and the last point were taken at two depths, 0-15 cm and 15-25 cm. All samples were taken with a shovel.

Soil analyses

Soil analyses were conducted at Tolima University in Colombia between 24 November and 6 December 2014. Respiration rate was not measured for Farm 1, MC.

Measurement of respiration rate

Soil respiration rate was measured by letting carbon dioxide, CO$_2$, emitted from moist soil be trapped by absorption in Sodium hydroxide (NaOH) solution. The principles of this method are described by Rowell (1994).

The soil samples was treated after being kept in an open plastic bag for 2 days, except from the samples from farm 1, which was kept an additional day. The field moist sample was
pushed through a 2 mm sieve. Of each soil sample 100 g was placed inside a jar that was set up to function as a respirometer. The soil was arranged at the bottom of the respirometer so that there was a small space free from soil in the middle. 20 ml 0.3 M Sodium Hydroxide solution was placed in a 30 ml glass jar that was placed into the respirometer so that no soil was underneath it. The management of NaOH was performed so that the chemical was not exposed to the air more than 30 s. The jar was sealed with airtight film whereby the time was noted. The respirometer was stored in a dark place at a temperature of 20-25˚C during one week. The NaOH solution from each respirometer was transferred into a 250 ml conical flask together with 20 ml 1 M barium chloride and two drops of phenolphthalein. To determine the respiration rate of the soil the NaOH solution was titrated by 1 M Hydrochloric acid until colour change occurred. The volume used HCl was noted. The respiration rate was calculated according to formulas described by Rowell (1994).

**Measurement of soil organic matter content and soil moisture**

The organic material present in the soil samples was measured by ignition loss as described by Ulf Hanell (2014). Soil moisture was also measured in this process. The soil samples were thoroughly mixed and 20 g of each sample were dried overnight in 105˚C together with empty vessels. The weight of each sample was noted and the soil moisture content was calculated. The dry vessels were weighed separately, empty respectively filled with 4 g of the dry soil, and the weight was noted. The vessels with 4 g of soil sample were put in an oven for 2, 5 h at 550˚C. The soil together with the vessel was weight and the content of organic matter was calculated.

**pH**

The soil sample was put through a 4 mm sieve whereby 50 g of the soil was mixed with 100 ml distilled water and left overnight in a glass jar. De solution was stirred by a magnetic stirrer during 10 minutes on 500 rpm, the pH was then measured using a pH-meter (Hanell, 2014)

**Statistics**
Multiple regression analysis were conducted on the results of respiration rate, organic matter content and soil moisture. The analyses were performed using Analysis ToolPak in Excel.

**Results**

The following text, table and figures present the results. The respiration rate was not measured for the monoculture field at farm 1.

**Soil respiration rate**

Soil respiration rate per hour and g dry soil was higher in the agroforestry fields than the monoculture fields. The multiple regression analysis showed a significant negative effect on respiration of monoculture management at depth 0-15 cm, with a reduction of 41% (see Table 2 and figure 6).

![Figure 6](image.jpg)

**Figure 6.** The bars show the respiration rate calculated as μg CO₂ per g dry soil and hour. The standard deviation is shown on the bars.

When the respiration rate was calculated as respiration per hour and dry organic matter the agroforestry farms still show the highest respiration rate at depth 0-15 cm. The multiple
regression analysis shows a statistic significant negative effect on respiration of monoculture management at this depth, with a reduction of 48 % (See Table 2 and Figure 6). The monoculture field at farm 2 showed a drastic drop in relation to the other fields.

Table 2. The results from the multiple regression analysis testing the effect of a change in management (from agroforestry to monoculture) and effect of site (3 sites) on soil respiration on a dry weight basis and on a dry organic matter basis. In both cases there were a significant reduction in soil respiration rate when going from system with trees to monoculture coffee plantations.

<table>
<thead>
<tr>
<th></th>
<th>Coefficient ± SE</th>
<th>p</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agroforestry</td>
<td>4.36 ± 0.83</td>
<td>0.0002</td>
<td>0.52</td>
</tr>
<tr>
<td>Effect of Monoculture</td>
<td>−1.81 ± 0.58</td>
<td>0.009</td>
<td></td>
</tr>
<tr>
<td>Effect of Site</td>
<td>−0.27 ± 0.38</td>
<td>0.48</td>
<td></td>
</tr>
</tbody>
</table>

b) Respiration per g dry organic matter (µg CO₂ g dry organic matter⁻¹)

<table>
<thead>
<tr>
<th></th>
<th>Coefficient (± SE)</th>
<th>p</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agroforestry</td>
<td>26.8 ± 5.6</td>
<td>0.0004</td>
<td>0.49</td>
</tr>
<tr>
<td>Effect of Monoculture</td>
<td>−12.9 ± 3.9</td>
<td>0.006</td>
<td></td>
</tr>
<tr>
<td>Effect of Site</td>
<td>1.0 ± 2.5</td>
<td>0.69</td>
<td></td>
</tr>
</tbody>
</table>

**Soil organic matter and soil moisture**

Soil moisture in fields ranged from 25.5 to 36.4 % at depth 0-15 cm and 23.9% to 32 % at 15-25 cm (see Figure 7 and Table 3). No significant statistical effect of the management system on soil moisture content could be seen in the soils tested. Organic matter content ranged from 7, 8 to 18, 3 % and the results showed no significant effect of the type of management system in use.

Figure 7. Soil organic matter content (left) and soil moisture content (right) at the farms. The standard deviation is shown on the bars.
**pH**

The monoculture field in farm 2 had the lowest measured pH (4.7) of all fields and the agroforestry field at farm 3 the highest (7.18) at 0-15 cm. The two depths had similar pH at all fields (see Table 3).

Table 3. Results from the analyses of soil samples

<table>
<thead>
<tr>
<th>Farm</th>
<th>Farm 1, AF</th>
<th>Farm 1, MC</th>
<th>Farm 2, AF</th>
<th>Farm 2, MC</th>
<th>Farm 3, AF</th>
<th>Farm 4, MC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>4.49041, -75.28343</td>
<td>4.49041, -75.28343</td>
<td>4.48551, -75.27452</td>
<td>4.48551, -75.27452</td>
<td>4.40224, -75.33365</td>
<td>4.39977, -75.33373</td>
</tr>
<tr>
<td>Altitude</td>
<td>1590 m asl</td>
<td>1590 m asl</td>
<td>1782 m asl</td>
<td>1782 m asl</td>
<td>1740 m asl</td>
<td>1870 m asl</td>
</tr>
<tr>
<td>Soil moisture, weight %</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0-15 cm</td>
<td>35.9</td>
<td>31.9</td>
<td>28.9</td>
<td>36.4</td>
<td>29.7</td>
<td>25.5</td>
</tr>
<tr>
<td>15-25 cm</td>
<td>32.0</td>
<td>31.2</td>
<td>26.2</td>
<td>37.3</td>
<td>34.0</td>
<td>23.9</td>
</tr>
<tr>
<td>Organic material, %</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0-15 cm</td>
<td>14.7</td>
<td>13.3</td>
<td>10.3</td>
<td>18.3</td>
<td>16.6</td>
<td>7.8</td>
</tr>
<tr>
<td>15-25 cm</td>
<td>9.5</td>
<td>10.9</td>
<td>8.4</td>
<td>16.1</td>
<td>9.1</td>
<td>5.6</td>
</tr>
<tr>
<td>CO2 (μg) / (dry soil (g) x h)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0-15 cm</td>
<td>4.6</td>
<td>no data</td>
<td>2.8</td>
<td>1.9</td>
<td>4.0</td>
<td>1.8</td>
</tr>
<tr>
<td>15-25 cm</td>
<td>2.3</td>
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<td>1.0</td>
<td>0.7</td>
<td>1.7</td>
<td>1.0</td>
</tr>
<tr>
<td>CO2 (μg) / (dry org. material (g) x h)</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>0-15 cm</td>
<td>31.6</td>
<td>no data</td>
<td>27.1</td>
<td>10.4</td>
<td>28.0</td>
<td>22.7</td>
</tr>
<tr>
<td>15-25 cm</td>
<td>24.4</td>
<td>no data</td>
<td>11.6</td>
<td>4.4</td>
<td>20.2</td>
<td>18.3</td>
</tr>
<tr>
<td>pH</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>0-15 cm</td>
<td>5.97</td>
<td>6.55</td>
<td>4.90</td>
<td>4.70</td>
<td>7.18</td>
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</tr>
<tr>
<td>15-25 cm</td>
<td>5.52</td>
<td>6.17</td>
<td>4.95</td>
<td>4.65</td>
<td>6.52</td>
<td>5.95</td>
</tr>
</tbody>
</table>

**Discussion**

The main hypothesis tested were that coffee cultivation under agroforestry management shows higher microbial activity (i.e. respiration), organic matter content and soil moisture compared to coffee grown in monoculture. Furthermore it was hypothesized that the respiration rate increases in relation to the organic matter content in the soil. Since the study material consist of only six farms it is not possible to draw any general conclusions of the results concerning the effect of management system in coffee cultivations. All of the investigated coffee fields had other plants than coffee present at the field and the fertilization practices varied greatly between farms. The main characteristics that distinguished the agroforestry fields from monoculture were that the agroforestry fields had more and larger trees and a larger number of different tree species. The monoculture coffee fields had mainly banana intercropped, and these plants were, as explained by one of the farmers, not for the sake of shade but as an extra source of income.
The most obvious difference in results between agroforestry coffee and monoculture coffee could be seen in the microbial activity where all agroforestry farms showed higher respiration rate at depth 0-15 cm. This is expected since trees contribute with litter which favour the microbial activity (Ferreira Araujo et al. 2011; Zake et al. 2015; Bagyaray et al., 2015; Raisei & Beheshti, 2014). However no such clear correlation could be seen in this study since the soil at the monoculture field at farm 2 (2MC) showed a higher content of soil organic matter and soil moisture than all the agroforestry farms at depth 0-15 cm but a lower respiration rate compared to all the agroforestry farms. When calculated as respiration per organic matter 2MC had remarkably lower values than all the other fields indicating that the organic matter in this field had a particularly low activity. Soil moisture and organic matter content are both factors shown to correlate positively with respiration rate (Bae et al. 2012; Ferreira Araujo et al. 2011; Zake et al. 2015) while other studies shows that there are more factors at play such as the number of trees species and fertilization practices at the farm (De Souza et al. 2011b; Wang et al. 2014). The most comparable field to 2MC in terms of location, soil composition and fertilization practices was the agroforestry field at same farm (2AF). This field has a larger variety in tree species and also larger trees even though the trees where not very dense planted and mainly concentrated to the borders of the field. The organic matter content and soil moisture in this field (2AF) was lower which may be due to that it is situated higher up at the very steep hillside, with the monoculture (2MC) field situated just below. This may cause a downward movement of organic matter and water to the advantage of the monoculture field. The low activity in the organic material at the monoculture field (2MC) indicates that this organic material contains more stable compounds (humified matter) than the agroforestry farm which is consistent with the results of Barro Marrinho (2014). The higher respiration rate in the agroforestry field (2AF) may be due to higher diversity of tree species in this field and the presence of leguminous trees. It has previously been found that a large number of tree species (Wang et al) and in particular leguminous tree (Pimentel et al. 2011; Leon et al. 2006) favour the microbial activity per unit microbial biomass an hence the nutrient cycle and decomposition rate in soil. This higher turnover rate may also be a contributing factor to the lower content of organic matter in the agroforestry field (2AF). Forest-like conditions have shown to favour the respiration rate (Bae et al. 2012; Raisei & Beheshti, 2014) which may explain why the agroforestry field at farm 1 (1AF) showed the highest rate, since this field is highly overgrown and resembles a forest in its composition.
Soil moisture was only slighter higher in the agroforestry fields (except from 2AF) compared to the monoculture fields and no statistical significant effect of the management system on soil moisture content could be seen. There are a number of studies showing that agroforestry management increases soil moisture (Guimaraes et al. 2014; Lin, 2006) but that the effects of soil moisture on respiration is not as evident during wet seasons (Bae et al. 2012) and that the correlation of shade trees and microbial activity is dependent of the seasons (Pimentel et al. 2011). This study was conducted during the wet season in Colombia and it is very likely that the results would exhibit greater mutual differences if the study was performed during the driest period (July and August). It suggests that a more long term study extending over at least a year is necessary to fully see the different effects of the cultivation systems on soil fertility indicators. This is confirmed by Van Oijen et al. (2010) who highlight this need of long term studies. Furthermore since the change of organic matter content is a slow process (Eriksson et al, 2011) the respiration rate at some of the fields may be affected by the history of the farm. The monoculture field at farm 1 (1MC) was recently renovated to a monoculture field from being an agroforestry field which is likely to have affected the high soil organic matter content found at that field. It is also conceivable that the use of pesticides and fungicides may have affected the microbial activity at farm 2 and 4; however more covered data on the use of such chemicals is needed to further discuss that.

The Soil pH was within the common pH range for coffee production (4-6) in most of the fields (Vaast et. al, 2008). However farm 2 exhibited particularly low pH (4.65-4.95) compared to the other fields. This is also a factor that may have influenced the low respiration rate at this farm since acidity in soil has negative effect on soil bacteria (Eriksson et al. 2011). The use of nitrogen fertilizer as well as the inclusion of certain tree species can increase soil acidity (Tully, 2013). The management of farm 2 included application of chemical fertilizers every 4th month which may have caused the high acidity in both fields at this farm. The monoculture field at farm 1 (1MC) used similar amount of fertilizer but showed a higher pH than the agroforestry field at the same farm (1AF) which may be due to the young age of the system in use but also due to the high density of trees (leguminous trees in particular) in the agroforestry system (1AF) (Tully et al. 2013). When comparing farm 3 and 4, which had similar conditions in terms of location, the agroforestry field (3AF) showed a higher pH as well as higher organic matter content than the monoculture field. The organic matter content has a buffering effect in the soil and can therefore counteract acidification (Gliessman, 2007; Eriksson et al. 2011), which may the reason for the higher pH shown in 3AF. Agroforestry
system has previously been found to reduce the soil acidity in cultivations (Barros Marinho et al. 2014), but this effect is not visible in the results from this study. All the agroforestry fields in this study contained leguminous trees, which could have influenced these results. However since no comprehensive inventory was made in terms of density of trees and number of each variety, it is not possible to say anything about the effect of the selection of tree species on the acidity and the respiration rate. This is a field that would be of interest for further studies.

Limitations of the study and possible improvements

This study contains several sources of probable errors. Since there is relatively few numbers of farms and sampling plots at each farm no general conclusions can be drawn from the results. The respiration rate was only measured at five fields since the data from 1MC is missing due to shortage of time.

A pure comparison between agroforestry and monoculture coffee was not possible since the farms differed largely even within the two categories. To make a meaningful discussion concerning the effect of the composition of tree species and the use of fertilizations and pesticides it is necessary to make a more detailed and assured collection of data on these aspects. The use of an interpreter in the performance of the interviews is a possible source of errors because of the possibilities of misunderstanding. The selections of farms were affected by a changed security situation in the country due to a broken peace agreement between the government and the guerrilla. On advice from the staff at Tolima University we delimited the search of the farms to an area very close to Ibague which influenced the selection. The method of measuring respiration rate may have been a source of error since we did not have any previous experience in the execution of this method. The space where the jars were stored during the respiration process did not have a stable temperature. This may have affected the results since the respiration experiments from the different fields were started at different days.

In addition to the methods used in this study it would have been interesting to measure the conductivity as well as the content of nutrients in the soils. An extensive measuring of the yield would also be interesting to put light on how agroforestry management in coffee cultivations relates to the productivity of the system.
The extensive conversion from agroforestry coffee to coffee grown in monocultures that is currently happening in Colombia and other parts of Latin America may cause long term effects on soil fertility and may bring a decreased resilience and food security for millions of smallholding coffee farmers. In the light of a the alarming extinction of biodiversity taking place at the planet it is of great importance to explore food production systems that make the least possible impact on ecosystems while at the same time being highly productive. Since agroforestry appears to be a viable strategy to cope with these challenges further research concerning the effects of different coffee cultivation system is of big importance.

Conclusions
Due to the small volume of data included in this study it is not possible to draw any general conclusions. The results suggest a higher respiration rate in agroforestry coffee cultivations compare to coffee grown in full sun in the Andean area in Colombia. The study also highlights the importance of taking into account the specific characteristics of the location and the management of the investigated farm when making conclusions about the effects of agroforestry. It is also concluded that long term studies, extending over at least a year, is necessary to fully see the effects of the cultivation practice on soil fertility indicators in coffee farms.

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Figure 8. Images showing the vegetation at the study sites.
**Figure 9.** Images showing the soil at the study sites.